MISSION TO PLANET EARTH SCIENCE RESEARCH PLAN

- Land-Cover and Land-Use Change Research
- Seasonal-to-Interannual Climate Variability and Prediction
- Natural Hazards Research and Applications
- Long-Term Climate: Natural Variability and Change Research
- Atmospheric Ozone Research

V.1 – September 1996

MTPE

National Aeronautics and Space Administration

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OFFICE OF MISSION TO PLANET EARTH
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, DC 20546

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Introduction

The Mission to Planet Earth (MTPE) program was conceived almost a decade ago, in an era of growth in funding for global environmental research. The scientific framework for the program was broad and ambitious, with the overarching goal of integrating the earth and environmental sciences into an interdisciplinary study of earth system science. MTPE became a major observational and scientific element of the U.S. Global Change Research Program (USGCRP), a program that has significantly changed the style and technical content of earth science research in this nation and the world.

While the past three decades have brought remarkable advances in scientific understanding and public awareness of environmental issues in most of the world's industrial nations, such advances are not universal. In most developing and newly industrializing countries, environmental quality has not, and probably will not, become a priority in the near future. The demand for economic progress by burgeoning populations is driving policies which encourage natural resource depletion and rapidly increasing emissions of environmental pollutants. Viewing the Earth from space is essential to comprehending the cumulative influence of human activities on its natural resource base. The science and observations of MTPE will become increasingly important in the years to come. Remote sensing also has the potential for dramatically improving crop and forest yield predictions, seasonal and interannual climate forecasts, urban planning, mineral exploration, and many other activities of socioeconomic importance. This potential has scarcely been tapped.

Interest in the use of remote sensing technologies for earth science and applications has been growing rapidly in Europe, Japan, Brazil, India, China, Korea, and many other countries. The U.S. could lose its leadership in this vital area of science and technology as these other countries move aggressively to utilize space observation technologies more effectively than we are doing. Accurate information on the state and health of the Earth's life support systems will move global society to more efficient markets for goods and services, thereby improving the quality of life. U.S. commercial and economic policy interests are increasingly a function of what goes on in the world marketplace, and the MTPE program will play an important role in the sustainability of national technological and commercial leadership.

We are in a period when government support for science and technology is declining, and MTPE and the USGCRP must work with the scientific community to make difficult choices. The forces which drive global change have not subsided, and societies worldwide are looking to the power of science and technology for solutions to the 21st century problem of expanding prosperity to a broader community of humankind. The challenges of increasing food production, managing natural resources like water and wood in a sustainable manner, and designing an eventual transition to renewable energy supplies demand practical solutions. Changes in the climate system, whether of natural or human-induced origin, must also be forecast with improved skill to improve agriculture and reduce economic impacts of floods, droughts, and other weather-related hazards. Success in moving toward environmental and economic security for the U.S. and other nations will require a focus and consistency of effort like that which ended the forty-year cold war. To these ends, the MTPE is pleased to issue this Science Research Plan which targets five specific research issues for focused investment of program resources during the next five years. A complementary implementation plan for the MTPE, including the Earth Observation System (EOS), is also in preparation. This document addresses the broad scientific framework for the entire MTPE program; the implementation plan addresses the contribution that the EOS observations will make to specific research issues.

An important priority is to provide an accurate assessment of the extent and health of the world's forest, grassland, and agricultural resources. In a time of rapid, and often unrecorded, land-use change, observations from space are

the only source of objective information on the human use of land. A closely related priority is to improve understanding and prediction of seasonal-to-interannual climate variation. Reducing uncertainties in climate predictions to a season or a year in advance will dramatically improve the efficiency of water use for agriculture and hydropower, as well as improve contingency planning for energy demand and other economic sectors. In addition, our natural hazards research priority places emphasis on the use of remote sensing observations for the characterization and mitigation of drought and flood impacts. There is increasing evidence that predictions of extreme weather events can be improved by understanding their links to interannual climate phenomena like the El Niño events. The MTPE science plan also calls for special attention in measuring and modeling the relative influence of forcing factors like clouds, aerosols, and greenhouse gases in long-term climate change, in order to improve our understanding and prediction of climate on time scales of decades to centuries. A continuing priority area for MTPE is understanding the causes and consequences of changes in atmospheric ozone. We will continue to make excellent progress on resolving questions related to stratospheric ozone depletion, and we are now emphasizing the changing composition of the lower atmosphere, which is especially sensitive to the unprecedented growth of pollutant emissions in East Asia and other rapidly developing regions.

This science plan also includes brief descriptions of the ongoing core research programs in MTPE. These programs provide the disciplinary strength that we draw from to solve interdisciplinary priority problems. We will continue to support these core programs to the extent possible, especially where the basic science enhances the understanding and value of remotely sensed information.

National needs and budget circumstances require the balance of effort in the MTPE program be changed from the original plan launched in an era of growing NASA budgets and federal support for global environmental research. An objective of current planning is to achieve the most essential long-term objectives of EOS, and to increase effort on science with near-term payoff, within a sustainable level of funding. In addition to the science focus described above, the observational program will become resilient, better, and cheaper in the future by— (1) Taking advantage of the experience being gained in the preparation of the first round of EOS flight missions to reduce observing requirements in the future and to simplify the design of instruments for more cost-effective continued operation. (2) Finding alternative means to carry out some of the essential measurements at the same level of quality through cooperation with other agencies and nations. MTPE is leading the discussion of a proposed Integrated Global Observing Strategy based on international agreement and task sharing. (3) Infusing new ideas and technologies into the EOS program through small satellite missions which have considerably lower infrastructure and flight costs.

The road ahead will be a difficult one. Budget reductions, redesigns and changes in the scientific scope to MTPE will surely continue as the Nation struggles to define its post cold-war direction, and unexpected events occur. This Science Research Plan will be the "roadmap" to developing the strongest and most productive MTPE research program that can operate effectively within these constraints. We urge each member of the scientific community to read the Plan carefully and send comments to the lead authors of each section who are identified. The plan will also be regularly reviewed by appropriate Boards and Committees of the National Academy of Sciences/National Research Council. It is more important than ever to identify, and concentrate on, research areas that promise major advances in societal benefits. The Nation expects and deserves a strong return on its investment in Mission to Planet Earth and the U.S. Global Change Research Program.

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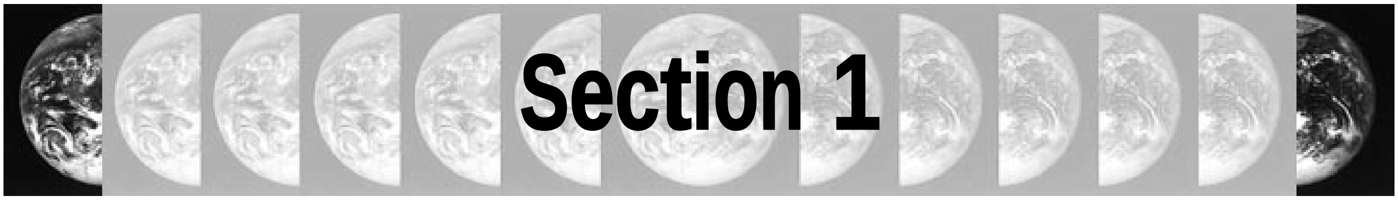

Section 1

Land-Cover and Land-Use Change Research

EXECUTIVE SUMMARY

There are very few landscapes on Earth that have not been significantly altered or are not being altered by humans. The current pattern of land-cover most often reflects past and present land-use. The larger patterns of land-cover are observable and can be monitored from space. From historical archives, including the last twenty years of satellite data, one can build a quantitative assessment of landscape and land-use change. More subtle types of change which take place, for example, through intensification of human use require additional *in situ* information.

Changes in land-cover and land-use are pervasive, increasingly rapid, and have a suite of interactions with the physical climate system, Earth system biogeochemistry, coastal and marine systems, and human societies. The oceans, especially coastal waters, are important resources for humanity beyond food and respiration needs, including transportation, energy and recreation. Nearly half the global population resides in coastal regions, and the coastal biosphere is increasingly impacted through anthropogenic activities, both intentional and accidental.

Changes in land-cover and land-use are driven largely by human societies, and are already beginning to threaten the continued provision of ecological goods and services. Changes in land-cover and land-use have impacts and implications at local, regional and global scales because of the way they alter biophysical, biogeochemical and hydrological states and processes. In the future, increasing pressure for land and food will lead to changes in land-cover and land-use and associated ecosystem processes in ways that currently cannot be well predicted.

The MTPE Land-Cover and Land-Use Change Strategy will provide some of the underlying science to permit assessments of the current distribution of land-cover and land-use, the changes that have taken place in the last several decades, the impact of those changes on biogeochemical cycling, biophysical processes, biodiversity, trace gas and particulate fluxes, coastal zone conditions, and the likely impacts of future land-cover change. It will address scientific questions relevant to and in some cases critical for sustainable land management and the provision of ecological goods and services.

The underlying philosophy of the MTPE Land-Cover and Land-Use Change Strategy is to understand the consequences of land-cover and land-use change for continued provision of ecological goods and services.

The ultimate vision is to develop the capability to perform repeated global inventories of land-cover and land-use from space, and to develop the scientific understanding and models necessary to evaluate the consequences of observed changes.

Components of the Strategy

1 FORCING FACTORS

These are the factors that drive changes in landscapes. They can be broadly separated into:

a. Climatic and ecological drivers: Both short and long-term variability in weather, climate, seismic activity, and internal ecosystem dynamics drive some aspects of land-cover change on multidecadal time scales. These drivers must be taken into account in any attempt to understand current patterns of land-cover and land-use, and also must be taken into account in any attempts at projection.

The NASA strategy is primarily to rely on basic research programs in seasonal-interannual climatic variability and long-term climatic change for historical and climatic data sets, although particular data sets for case studies may be supported, on a case-by-case basis.

b. Socioeconomic drivers: This category includes the economic, social, and political factors that fuel the human activities responsible both for conversion of landcover and for intensification of management regimes. Desires around the world for economic development, and needs around the world for increased food production and delivery must be quantified, understood, and ultimately modeled. Any attempt to understand current patterns of land-cover and land-use must explicitly take into account land-use history.

The NASA strategy will be to investigate the human dimension processes directly when they can be coupled to observed recent changes in the landscape.

2 Responses and Consequences

The NASA strategy recognizes that the future stresses of population pressure, expansion of urban areas, and economic development are largely occurring in the developing world in the tropics and sub-tropics. Thus, NASA proposes to make the intial thrust of its effort in those parts of the world that are both currently undergoing the most stress, and where the stresses from human activities are sure to increase the most rapidly. There are two broad categories of responses to the drivers of change of particular importance to the NASA program:

a. Land-cover conversion: The primary NASA interest is to identify the current distribution of land-cover types, and to track their conversion to other types. Of particular interest because of the links to trace gases is being able to measure the rates of rapid conversion of forest cover to other types, as is occurring in the humid tropics.

b. Land-use intensification: A primary interest of the LCLUC strategy will initially be in understanding the consequences of intensified management of agricultural and agroforestry systems, particularly in the tropics and sub-tropics, and being able to measure the longer-term, *in situ* degradation of forested ecosystems that occurs through such activities as logging, imprudent forest management, etc.

c. Land degradation in arid and semi-arid environments: The issue of land degradation is crucial to the sustainability of human society. Land degradation affects the ecology and food supply potential of regions which will need to support growing human populations. The NASA strategy addresses the need to define, develop, and evaluate improved remote sensing measurement techniques and data integration methods for characterizing land degradation due to salinization, desertification, erosion, and other consequences of unsustainable land uses and/or extreme climate variability.

d. Consequences of international agreements: There is the potential for increased emphasis on forestry and agriculture in temperate and boreal systems, as the implications of the Climate and Biodiversity Conventions for forests and agriculture become better understood by individual countries.

3 Modeling and Implications

We anticipate that an important contribution of the LCLUC Strategy will be the development of techniques to incorporate land-use change into existing biogeochemical and biophysical models.

4 Techniques and Methods

An important part of the overall strategy will be to develop, refine, and implement techniques and methods in basic remote sensing and information science in support of the science objectives of this program.

Priorities for Case Studies

U.S. and the Americas: The LCLUC strategy supports development of new and improved land-cover and land-use data for the U.S. at regional and continental scales.

Amazon: A major focus of research activities within the LCLUC strategy are the NASA contributions to the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA).

Southeast Asia: A base of scientific investigations must be built within Asian and Southeast Asian countries that will assess the consequences of forest conversion to agriculture, the long-term, *in situ* degradation of the forested landscape, and agricultural intensification.

Southern and Central Africa: The land transformations currently going on in the dense humid forests, the seasonal woodlands, and savanna systems of Africa are of considerable interest in the LCLUC strategy, require initial planning efforts, and a small, focused research investment.

Russia and the Countries of the Former Soviet Union: The primary LCLUC efforts in this region will be to take advantage of data sets and studies that have been developed within the context of the Earth Sciences Joint Working Group, and to coordinate activities with those of other agencies with particular interests in the boreal forest.

Reporting

We envision that the Land-Cover and Land-Use Change Strategy will develop a series of reports that identify the consequences of land-use change in globally important areas of rapid change, and that these reports will provide the scientific foundation for a new NASA series of reports on human influences on the biosphere.

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MTPE LAND-COVER AND LAND-USE CHANGE STRATEGY

I. Introduction

This document describes a research strategy within NASA's Mission to Planet Earth (MTPE) that addresses the magnitude and impacts of land-cover and land-use change. The strategy builds on current research and development within MTPE. It uses a combination of *in situ* measurements and existing and planned satellite systems to provide policy-relevant information. As part of the strategy, an initiative will provide new starts aimed at filling the larger gaps in current understanding of the impacts of land-cover and land-use change.

II. Background

The underlying philosophy of the MTPE Land-Cover and Land-Use Change Strategy is to understand the consequences of land-cover and land-use change for continued provision of ecological goods and services.

The ultimate vision is to develop the capability to perform repeated global inventories of land-cover and land-use from space, and to develop the scientific understanding and models necessary to evaluate the consequences of observed changes.

The preservation of ecological goods and services depends on sustainable management of resources, and recognizes three facts:

1. Ecological processes controlling biogeochemical cycles and hydrologic processes result in both goods, i.e. food, fiber, etc., and services, e.g., water purification, preservation of soil fertility;

2. Human influences that both transform land cover from one type to another and that change or intensify the management regime on lands clearly affect provision of goods and services regionally, and have the potential to affect them globally; and therefore

3. It is necessary to understand the human influence on these processes to determine the potential for continuing provision of resources and services for expanding human populations.

There are very few landscapes on Earth that have not been significantly altered or are not being altered by humans. The current pattern of land-cover most often reflects past and present land-use. The larger patterns of land-cover are observable and can be monitored from space. From historical archives, including the last twenty years of satellite data, one can build a quantitative assessment of landscape and land-use change. More subtle types of change which take place, for example, through intensification of human use require additional *in situ* information.

Changes in land-cover and land-use are pervasive, increasingly rapid, and have a suite of interactions with the physical climate system, Earth system biogeochemistry, coastal and marine systems, and human societies (Fig. 1-1). The oceans, especially coastal waters, are important resources for humanity beyond food and respiration needs, including transportation, energy and recreation. Nearly half the global population resides in coastal regions, and the coastal biosphere is increasingly impacted through anthropogenic activities, both intentional and accidental.

Changes in land-cover and land-use are driven largely by human societies, and are already beginning to threaten the continued provision of ecological goods and services. Changes in land-cover and land-use have impacts and implications at local, regional and global scales because of the way they alter biophysical, biogeochemical and hydrological states and processes. In the future, increasing pressure

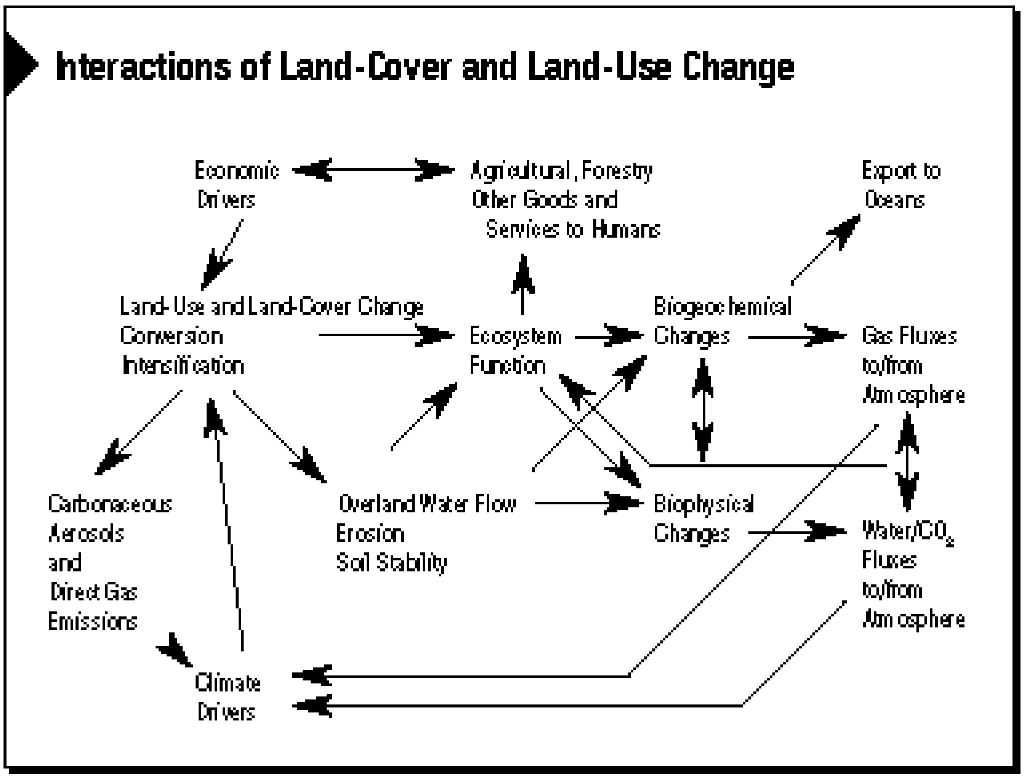


Fig1-1

for land and food will lead to changes in land-cover and land-use and associated ecosystem processes in ways that currently cannot be well predicted.

The driving forces of land-cover and land-use change arise from a combination of socioeconomic and physical factors. These factors are often poorly understood and modeled by the scientific community. A better understanding of the factors controlling land-cover and land-use change will improve the development of models which can then be used to evaluate various options for improved land-use and management.

The MTPE Land-Cover and Land-Use Change Strategy will provide some of the underlying science to permit assess- ments of the current distribution of land-cover and land-use, the changes that have taken place in the last several decades, the impact of those changes on biogeochemical cycling, biophysical processes, biodiversity, trace gas and particulate fluxes, coastal zone conditions, and the likely impacts of future land-cover change. It will address scientific questions relevant to and in some cases critical for sustainable land management and the provision of ecological goods and services.

Accurately accounting for land-cover and land-use change with fine spatial and temporal resolution, as well as the underlying research to interpret it, will require partnerships of many scientific and natural resource management institutions around the world. While some of the necessary measurements can be made from space, the scientific understanding required to interpret and evaluate these observations cannot be generated only through remote sensing, and thus demands such partnerships. The role of the space-based components will primarily be to develop methods to extend local and regional understanding to global scales. Space agencies around the world will need to coordinate their efforts to help achieve this vision, which might have its scientific underpinning articulated by GCOS, IGBP, and WCRP, and could be implemented by the CEOS agencies. The role of the *in situ* components will be to develop methods, measurements, and the understanding necessary to translate observed changes into verifiable predictions and reasonable scenarios that are ultimately useful to resource managers in both public and private sectors. Scientific and natural resource agencies around the world will likewise need to coordinate their activities not only with each other, but also with the space agencies to

build the desired links between the underlying science and its applications to real-world management concerns.

NASA's role will be to develop methods, techniques, and sponsor research that demonstrates the consequences of land-use change, establishes ways to quantify them, and develops the capabilities to explore alternative land use and monitoring strategies. This research will provide scientific understanding and tools for future operational and commercial interests in land and ocean remote sensing.

III. Components of the Strategy

There are four underlying components to the NASA MTPE Land-Cover and Land-Use Change Strategy. Below is a short description of each.

1 Forcing Factors

These are the factors that drive changes in landscapes. They can be broadly separated into:

a. **Climatic and ecological drivers:** Both short and long-term variability in weather, climate, seismic activity, and internal ecosystem dynamics drive some aspects of land-cover change on multi-decadal time scales (Fig. 1-2). These drivers must be taken into account in any attempt to understand current patterns of land-cover and land-use, and also must be taken into account in any attempts at projection.

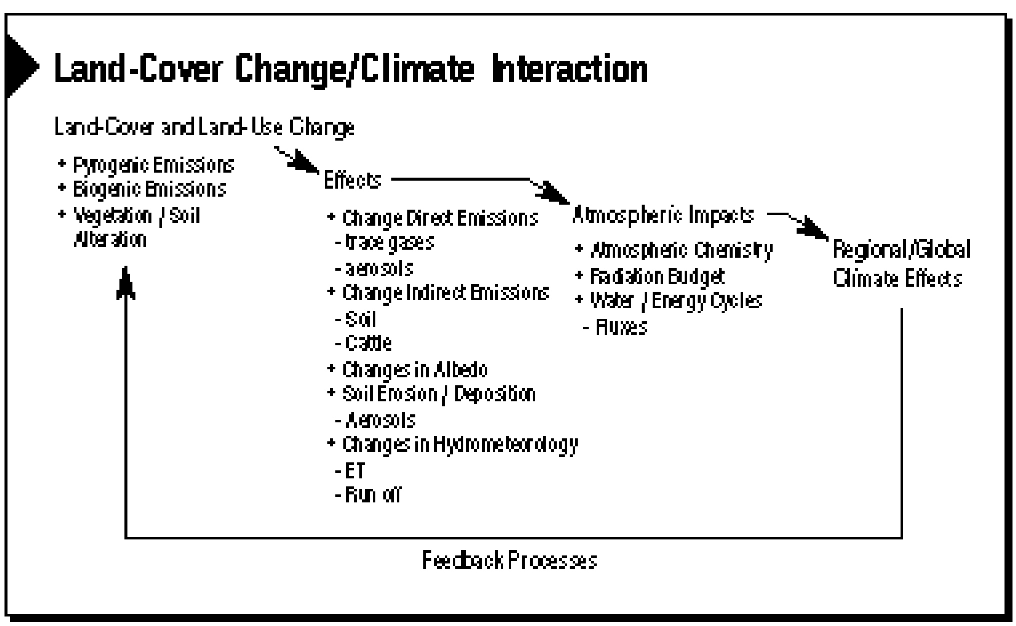


Fig 1-2

The NASA strategy is primarily to rely on basic research programs in seasonal-interannual climatic variability and long-term climatic change for historical and climatic data sets, although particular data sets for case studies may be supported, on a case-by-case basis. Current research programs on seasonal-interannual climatic variability and long-term climate change in NASA's MTPE and more broadly in the U.S. Global Change Research Program provide a wealth of climatic data both for the U.S. and other regions of the world. Analogous historical data on vegetation and ecosystem dynamics come from research and monitoring programs within both science and natural resource management agencies. These data will be incorporated into case studies in the Land-Cover and Land-Use Change Strategy.

Over the next several years, the contributions of TRMM, SeaWiFS, EOS AM-1, and Landsat-7 will be expected to provide quantitative, space-based data on the climatic regimes and underlying vegetation dynamics around the world. The acquisition of new digital elevation data for EOS AM-1, and the continuing improvement of DEM data around the world will also be a necessary part of the NASA program.

b. Socioeconomic drivers: This category includes the economic, social, and political factors that fuel the human activities responsible both for conversion of land-cover and for intensification of management regimes (Fig. 1-3). Desires around the world for economic development, and needs around the world for increased food production and delivery must be quantified, understood, and ultimately modeled. Any attempt to understand current patterns of land-cover and land-use must explicitly take into account land-use history.

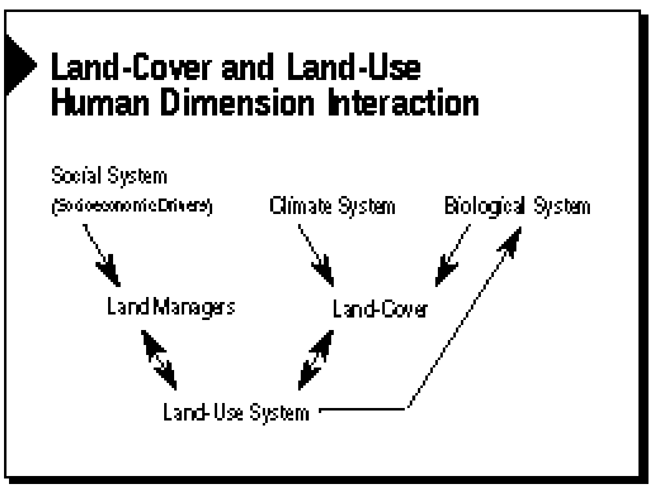


Fig 1-3

The NASA strategy will be to investigate the human dimension processes directly when they can be coupled to observed recent changes in the landscape. The NASA programs will be linked to other research on human dimensions of land-use change both within the U.S. and abroad. Particular data sets for case studies will be supported by NASA on a case-by-case basis. However, the NASA strategy depends on having close interdisciplinary ties to domestic and international research programs in the human dimensions, so that both the ultimate social causes and consequences of land-cover and land-use change can be understood.

2 Responses and Consequences

The NASA strategy recognizes that the future stresses of population pressure, expansion of urban areas, and economic development are largely occurring in the developing world in the tropics and sub-tropics. Thus, NASA proposes to make the intial thrust of its effort in those parts of the world that are both currently undergoing the most stress, and where the stresses from human activities are sure to increase the most rapidly. There are two broad categories of responses to the drivers of change of particular importance to the NASA program:

a. Land-cover conversion: *The primary NASA interest is to identify the current distribution of land-cover types, and to track their conversion to other types. Of particular interest because of links to trace gases is being able to measure the rates of rapid conversion of forest cover to other types, as is occuring in the humid tropics*. These data can be used in the development and verification of biogeochemical and biophysical models, and also in the analysis of the effect of spatial patterns and history of conversion on ecosystem processes and structure, on the effects on biodiversity at a variety of scales of analysis, and on the effects on the continued delivery of ecological services on local-landscape-regional scales. The data will additionally be critical to identifying the types of land-cover in which *in situ* process and ecosystem studies need to be performed inorder to parameterize landscape-scale (and larger) ecosystem models, and to understand the current patterns of biogeochemical and biophysical functioning on the landscape. Links to patterns and changes in tropospheric chemistry and possible changes in large-scale hydrometeorology can easily be explored in this arena. Methods for tracking land-cover conversion have been developed through the Landsat Pathfinder Humid Tropical Forest activity. Methodological improvements can be achieved, but there is a current core of workable methods

b. **Land-use intensification:** *A primary interest of the LCLUC strategy will initially be in understanding the consequences of intensified management of agricultural and agroforestry systems, particularly in the tropics and sub-tropics, and being able to measure the longer-term, in situ degradation of forested ecosystems that occurs through such activities as logging, imprudent forest management, etc.* These data can help understand the consequences of managing the end-states of land-cover change. Detecting *in situ* degradation is difficult. Current research in the Landsat Pathfinder suggests that while Landsat can be used to detect the presence of intensive logging, additional methodological and technological research may be necessary to arrive at consistent and defensible estimates of long-term degradation. Detection of phenomena such as long-term change in the frequency of fire in forests or savannas will require both good historical data, and also improvements in satellite measurement techniques. Several of these techniques are under development in both NASA programs and in other agency programs.

c. **Land degradation in arid and semi-arid environments:** The issue of land degradation is crucial to the sustainability of human society. Land degradation affects the ecology and food supply potential of regions which will need to support growing human populations. *The NASA strategy addresses the need to define, develop, and evaluate improved remote sensing measurement techniques and data integration methods for characterizing land degradation due to salinization, desertification, erosion, and other consequences of unsustainable land uses and/or extreme climate variability.*

   Remotely sensed data such as Landsat Thematic Mapper (TM), Spot Panchromatic and Multispectral, Lewis Hyperspectral, Clark Panchromatic, and data from other satellite and airborne sensors can facilitate the monitoring, quantifying, and forecasting of land degradation. *In situ* data on weather and climate, land use practices, population, and other relevant variables can be fused with remote sensing data using GIS techniques.

   Geographic areas of special interest include the U.S.-Mexico border region, regions important to U.S. agricultural productivity, the Nile Delta, the Yangtze Delta of China, and any other areas where land degradation poses a threat to sustainable food production for growing populations.

d. **Consequences of international agreements:** *There is the potential for increased emphasis on forestry and agriculture in temperate and boreal systems, as the implications of the Climate and Biodiversity Conventions for forests and agriculture become better understood by individual countries.* There are many opportunities for the NASA science programs to develop interactions with a variety of country case studies, as well as with other U.S. programs in the land management agencies. These links will be especially important in building up the history of land management in particular case studies, which has not been a major strength of NASA-sponsored research. Links to other process studies in tropospheric chemistry, hydrometeorology, and riverine dynamics will stimulate further the development and evaluation of coupled Earth system models.

3 Modeling and Implications

We anticipate that an important contribution of the LCLUC Strategy will be the development of techniques to incorporate land-use change into existing biogeochemical and biophysical models. It will be important to develop, parameterize, and evaluate models that are able to couple the biogeochemical and biophysical dynamics of the land surface and its interactions with the atmosphere (Fig. 1-4). This is a generally well-developed program within the overall MTPE science activities. The new emphasis from the perspective of land-cover and land-use change will be the development of data sets and techniques to enable the models to use better repre-

sentations of the actual land-cover present, rather than potential natural vegetation, and therefore to be able to represent changes in land-cover, whether from the internal dynamics of the ecosystems, or from human-driven perturbations. The ecosystem model intercomparison program of VEMAP for the U.S., and the international primary productivity model intercomparison program of GAIM will be important clients.

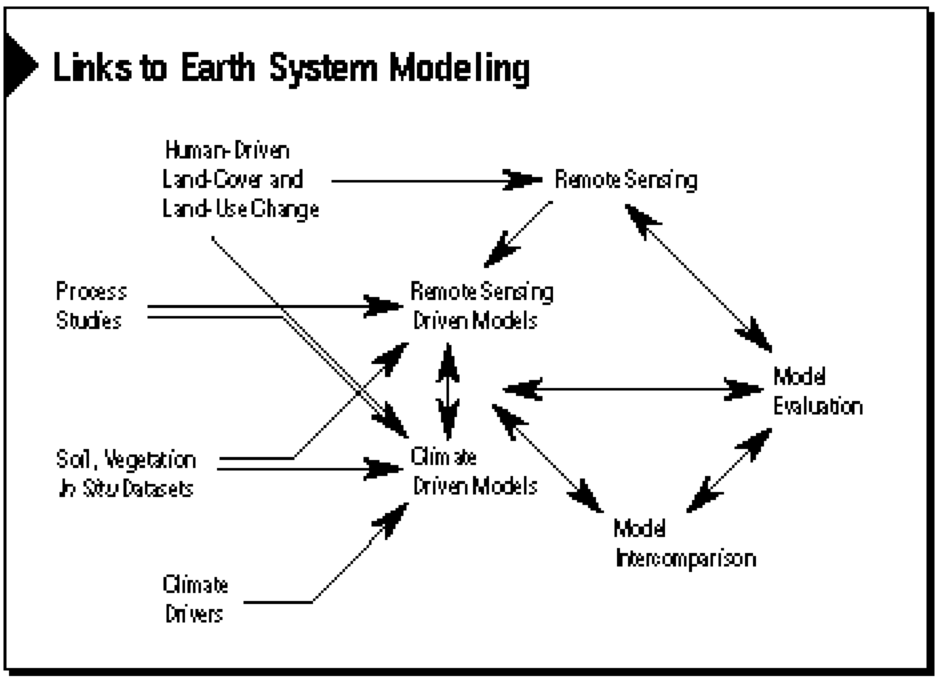


Fig1-1

Ultimately, it will be the ability to model systems undergoing land-use change that will provide tools for both scientists and decision-makers to evaluate the potential consequences of different management practices, and to assess the consequences of policies that affect land-cover conversion. There will be close ties of the new initiative on Land-Cover and Land-Use Change to the existing and developing efforts in Earth System Modeling, sponsored through MTPE Science and the EOS IDS teams.

4 Techniques and Methods

An important part of the overall strategy will be to develop, refine, and implement techniques and methods in basic remote sensing and information science in support of the science objectives of this program. The current vision is that this component of the overall strategy will encompass both advances in the basic physical understanding and modeling of remote sensing and advances in information systems. Both are ultimately necessary to achieve a productive interaction with policy and natural resource management communities.

Techniques and methods for applying satellite data to address questions of land-cover and land-use change are being developed in various parts of current NASA programs. Close coordination will be sought as part of this strategy with the algorithm development and testing being supported by the remote sensing science component of the NASA Terrestrial Ecology Program, with the NASA Pathfinder Program, and with EOS Interdisciplinary Science and Instrument Science Teams. This new strategy will provide a focus for these activities and should make use of the global archives of high resolution satellite data acquired over the last twenty years for addressing land-cover and land-use change. Coarse resolution satellite time series data may also be used to improve land-cover classifications suitable for use in global and regional models. One particular area where methodological progress is urgently needed is the combination of physical and socioeconomic data in process and predictive modeling of land-cover change at a regional scale.

IV. Priorities for Case Studies

In addition to the topical areas of importance to the overall LCLUC strategy, the initiation of research projects in particular areas and regions will help develop concrete examples of the interactions of natural and human dynamics. Because many of the major recent, rapid changes in land-use have been in the tropics and sub-tropics, and are expected to continue to be, we anticipate that there will be an initial emphasis in those regions (Fig. 1-5). The primary consideration of the location of the in situ research will be to have sites representative of the major landcover types identified in the intial studies of landcover conversion, as well as those areas undergoing intensification of management activities. Initial priorities for case studies are identified below:

U.S. and the Americas: *The LCLUC strategy supports development of new and improved land-cover and land-use data for the U.S. at regional and continental scales*. In addition, NASA is interested in well-documented regional case studies that couple land-use, land-cover, atmospheric and climate data, and ecosystem modeling in order to evaluate the response of ecological systems to multiple stresses. Studies that provide insight into the vulnerabilities of ecosystem goods and services to a combination of anthropogenic stresses, management regimes, and climatic variability will receive priority. Special attention will be given to projects that can demonstrate an understanding of the influence of local and regional management decisions on the functioning of the landscape.

Amazon: *A major focus of research activities within the LCLUC strategy are the NASA contributions to the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA)*. This field campaign will focus on two key questions: How does Amazonia currently function as a regional entity? And, how will changes in land use and climate affect the biological, chemical and physical functions of Amazonia, including the sustainability of development in the region and the influence of Amazonia on global climate? The LBA will provide a critical opportunity to investigate these issues with a combination of models, remote sensing, and *in situ* process-based studies. The particular enhancements that a LCLUC focus can bring to the LBA might include process-based studies to focus primarily on the consequences of long-term management of altered landscapes in Amazonia, and how these altered landscapes interact with unaltered vegetation. A wider variety of agricultural landscapes can be studied than would otherwise be possible, and the scope of investigations can be broadened to include consideration of the social, political, and economic factors affecting land-use change. Emphasis will be on the long-term consequences of actively managing the landscape in a mosaic of natural and human-dominated systems.

Southeast Asia: *A base of scientific investigations must be built within Asian and Southeast Asian countries that will assess the consequences of forest conversion to agriculture, the long-term, in situ degradation of the forested landscape, and agricultural intensification*. Projects that look at the interaction of agricultural areas, natural areas, and managed forests will be encouraged. These would include projects that investigate the capability of remote sensing to both map changes, and parameterize landscape-scale ecosystem models. Projects that demonstrate linkages to in-country scientists and direct links to regional IGBP projects will receive priority.

Southern and Central Africa: *The land transformations currently going on in the dense humid forests, the seasonal woodlands, and savanna systems of Africa are of considerable interest in the LCLUC strategy, require initial planning efforts, and a small, focused research investment*. The primary reason for beginning activities in this area is to synthesize results from international, European and South African sponsored campaigns in which NASA has been a small participant in order to understand which activities can be enhanced in conjunction with IGBP and the host countries. There are a few activities currently under way in the Terrestrial Ecology Program that are investigating processes along transects in this region. These may be viewed as planning activities for the future. The LCLUC regional activity will be developed and implemented in conjunction with international programs such as the USAID Central Africa Project for the Environment (CARPE), IGBP, LUCC and START and the host countries. Projects that demonstrate linkages to in-country scientists and direct links to regional IGBP projects will receive priority.

Russia and the Countries of the Former Soviet Union: *The primary LCLUC efforts in this region will be to take advantage of data sets and studies that have been developed within the context of the Earth Sciences Joint Working Group, and to coordinate activities with those of other agencies with particular interests in the boreal forest.* There are several potential areas of interest: one is to understand whether or not frequencies of major fires in the boreal region have increased over the past several decades, which has been hypothesized. Another is to be ready to evaluate the consequences for the global carbon cycle if large tracts of boreal forest are logged for timber as a result of the concessions that have been sold to Japan. A third is to conduct careful case studies of agricultural and forested regions, concentrating on the effects of past management practices; this may become possible because of data sets that are now becoming available. Such projects should demonstrate linkages to in-country scientists and direct links to regional IGBP projects.

V. Reporting

We envision that the Land-Cover and Land-Use Change Strategy will develop a series of reports that identify the consequences of land-use change in globally important areas of rapid change, and that these reports will provide the scientific foundation for a new NASA series of reports on human influences on the biosphere. NASA will form a Land-Cover and Land-Use Change Science Team from investigators selected through the first solicitation of the initiative, as well as selected investigators from other peer-reviewed projects and programs within Mission to Planet Earth and appropriate programs in other Federal agencies. The Science Team will meet at least once a year as a whole to review progress, report results, and advise Mission to Planet Earth on new research directions. In addition, the Science Team will be expected to advise NASA on a variety of research topics related to land-cover and land-use change. For example, the Science Team might be asked to evaluate the degree to which land-surface classification algorithms for research and operational purposes ought to be synchronized.

A specific charge to the Science Team will be to develop a series of reports and assessments on the consequences of land-use change in different parts of the globe. These reports will go beyond the expected high number of scientific refereed papers from this program and will be targeted at high-level decision-makers and the public. The reports will be along the lines of integrated assessments closely tying the science to improved resource and environmental management. The outline for this new series of reports will be developed over the next year, along with a detailed plan for how information from NASA and other programs will be used.

VI. Links to Pathfinder and other Data-Development Efforts within MTPE

The links to the Pathfinder and other data-development efforts within MTPE are extremely important. Because of the proposed tropical/subtropical initial focus, the Landsat Pathfinder Humid Tropical Forest activity provides the major foundation of data on land-cover conversion for both rapid and slower, *in situ* changes (Fig. 1-5). Thus, the science supported through the LCLUC Strategy builds on the observations and data sets provided and archived through Pathfinder. Funds set aside in EOSDIS for the purchase of commercial Thematic Mapper and SPOT data (and possibly other systems, e.g., IRS) should have the LCLUC Strategy as one of the major clients, with the Pathfinders acting as intermediary.

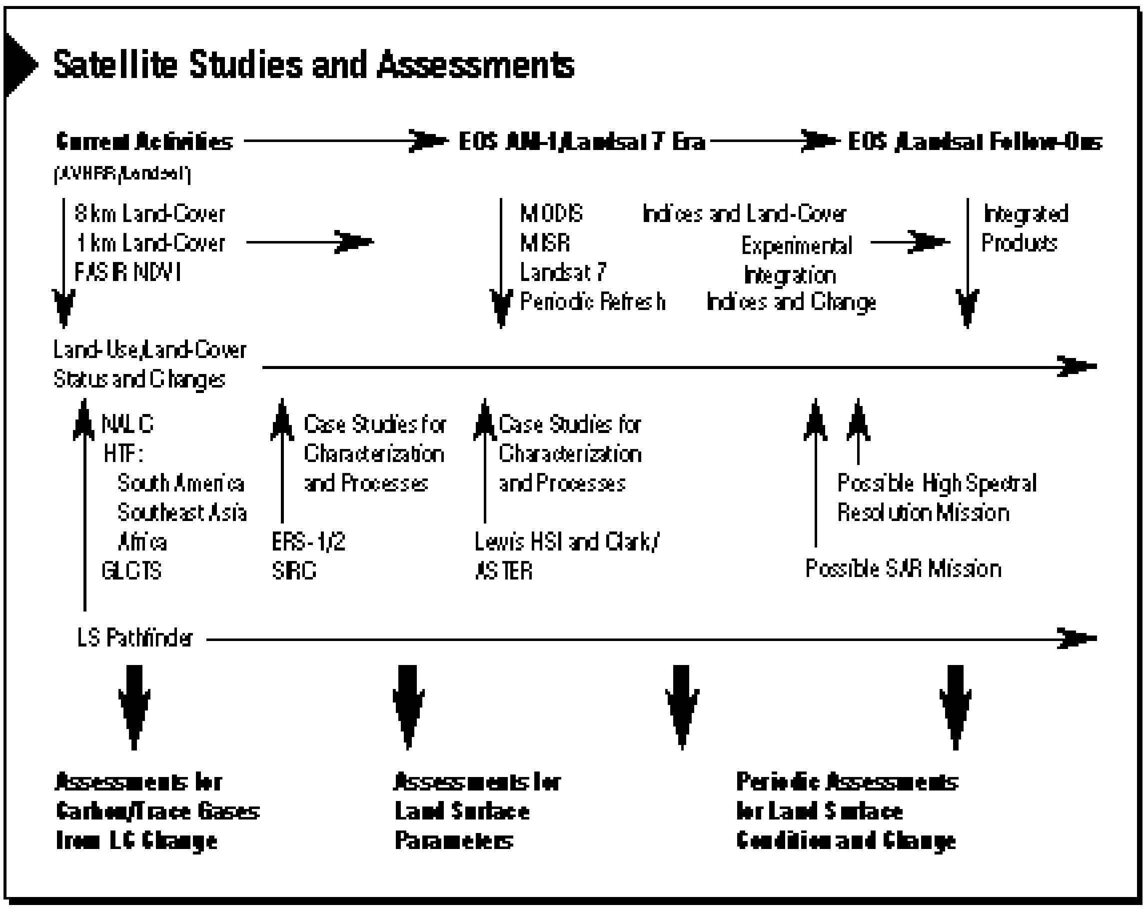


Fig 1-5

There are several MTPE investments in current activities to produce and make available global land-cover maps at different spatial resolutions. These provide important foundations for the land-use change efforts. In particular, the success of these projects in interpreting land-use from satellite data will provide a critical piece of information as we look ahead to the utility of the satellite measurements in the long-term. Other Pathfinder efforts, such as the GAC AVHRR and Global 1km project, may also play important roles, for example in global landcover mapping.

To address the challenges of multiple measurements of ocean color, and hence land-use change impacts in the coastal zone, NASA has created the special initiative called SIMBIOS to make best use of the scheduled missions by developing a methodology and operational capability to combine data products from the various ocean color missions in a manner that ensures the best possible global coverage, and exploits best the complementarity of the sensors. The specific objectives of SIMBIOS are (1) to quantify the relative accuracies of the products from international ocean color missions, (2) to improve the level of confidence and compatibility among the products and (3) to generate merged, improved level-3 products. To this end, a NASA Research Announcement has been released for SIMBIOS to solicit proposals for scientific investigations and activities in support of NASA's MTPE and EOS to provide routine, long-term ocean color data from the various international missions launched or scheduled for launch between 1996 and 2001. Awards are anticipated to be made in early 1997 for the various parts of the SIMBIOS project.

The SIMBIOS project encompasses both experimental and operational requirements with links to all the missions, but will have a separate management and facility structure. These activities have been organized into four basic components, namely sensor calibration, product and algorithm validation, data merging, and operational data processing. All components are connected (and in some cases overlap) and each illustrates the process of product development, assessment and refinement which is central to the SIMBIOS project.

VII. Links to Planned and Future Campaigns

An important part of the land-use change program will be the development of field-based campaigns that take advantage of MTPE measurement capabilities to understand the integration of changes on the land surface with chemical and physical properties of the atmosphere (Fig. 1-6). The most important initial study will be LBA. The LBA activities will span the range of interests from large-scale hydrometeorology, to mesoscale atmospheric phenomena, to transect-based studies of ecological and atmospheric biogeochemistry. Its underlying rationale is to understand the functioning of the Amazon Basin as an integrated system, with a particular focus on understanding how the rapid land-use change of the past few decades has affected it.

We can anticipate at this time that other integrated campaigns should be planned for Southeast Asia, possibly focusing on areas with landscapes affected by selected logging, intensified agriculture, and urban expansion. It is also likely that MTPE will at some point in the reasonably near future need to mount a campaign in sub-Saharan Africa, building on currently funded NASA research, to understand better the consequences of very different patterns of land-cover and land-use change there.

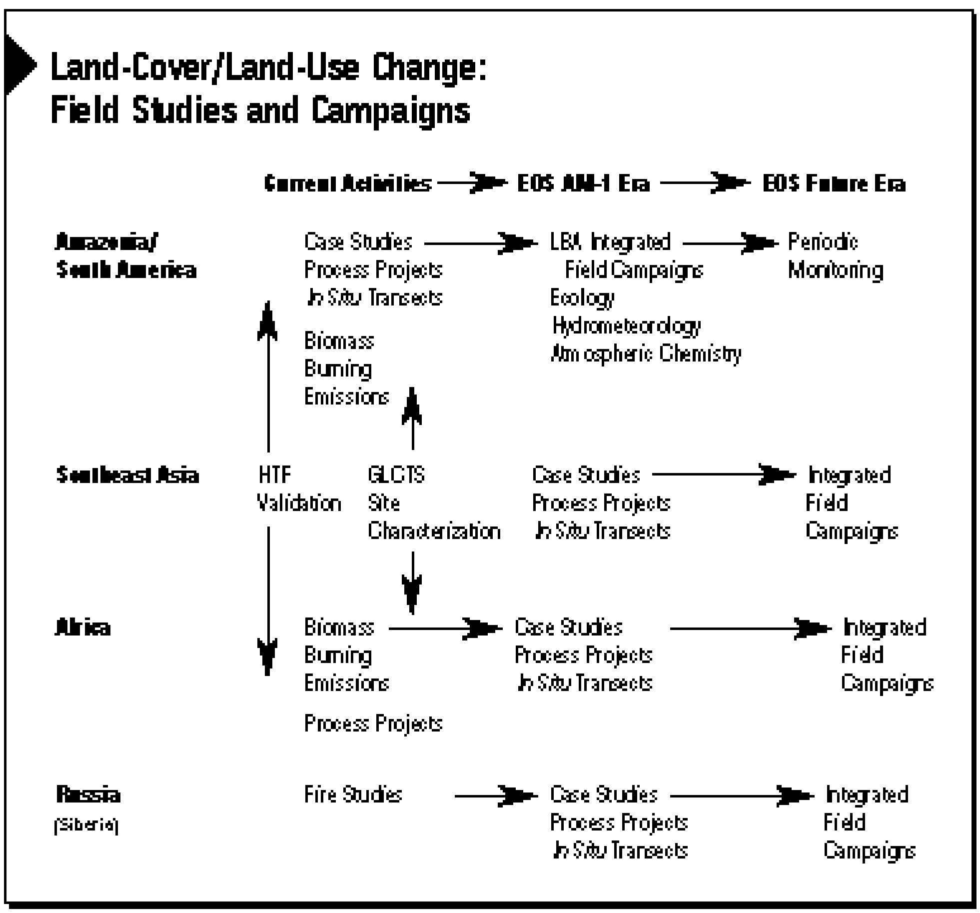


Fig1-6

Other, smaller campaigns should also be developed as a part of the Land-Cover and Land-Use Change Strategy. Specific integrated studies to investigate the links between remotely sensed data and biogeochemical/biophysical processes should be planned in order to develop and parameterize models on landscape scales. Models on these scales are likely to be of great importance in developing the confidence in parameterizations for models that examine changes on regional and global scales, and/or the transient response of landscapes over long time periods.

Because of the strong links to human interactions research, the land-use change program should have a natural interface to projects within or outside of NASA that attempt to couple socio-economic modeling to changes in land-use. Models to do this have already seen a substantial amount of development in agriculture and forestry, and there may be other opportunities as well. Models that combine energy sector economics with land-use related economics are not well developed, and could provide an interesting example to be investigated (Fig. 1-3 and 1-4).

VIII. Links to Earth System Modeling

The Earth System Modeling efforts within MTPE span a range of activities. However, one of the major goals of the suite of large projects is to produce a first-order coupling of biogeochemical and physical processes within the context of global system models. Within the IGBP, this goal is shared with the GAIM project. The interconnections with the development of techniques to represent actual land surfaces in such models, and to incorporate land-surface dynamics and change in them are obvious, and will be encouraged throughout the Land-Cover/Land-Use Change Strategy.

The second major goal of the Earth System modeling efforts within MTPE is to develop better techniques for data assimilation of the suite of satellite remote sensing data that will soon be available. Currently, concrete plans exist only for those data for which broad experience exists within the atmospheric physical climate community. While this perspective is broadening to include the oceans and some representations of the fast biophysical processes of the land surface, more attention is clearly needed to representing correctly changes in the land surface. This is clearly a topic on which research needs to be done, in order to develop and improve reasonable parameterizations that can be used, for example, with MODIS data, and which can then be incorporated into a broader data assimilation effort.

IX. Infusing New Technologies

NASA has long had the role of developing new technologies for the benefit of scientific users and for potential commercial users. There are several opportunities available for infusing new technological development and exploration into the study of land-use change. An obvious candidate is the exploration of the use of high spectral resolution remote sensing to understand two aspects of dynamic land surfaces: their accurate classification into different cover types, and possibly the chemical composition of their plant canopies, including their photosynthetic pigment complements and nitrogen status. Within the next several years, the Lewis technology demonstration mission will provide the first opportunity to evaluate the utility of high spectral resolution data derived on orbit. There is the further possibility of continuing the Terrestrial Ecology Program in its work to complete the scientific tasks begun by the HIRIS Science Team through use of AVIRIS and other hyperspectral imagers.

There are other new technological capabilities that ought to be explored, both in terms of potential new measurements, and in terms of new capabilities to provide data (Fig. 1-6). Ongoing projects in the Terrestrial Ecology Program that investigate the utility of SAR's for categorizing different land-cover types, and for deriving biophysical parameters from landscapes should continue to be pursued, but re-focused on issues of particular concern for understanding the consequences of land-use change. New technological capabilities for acquiring, processing, disseminating, and archiving data and information electronically also should be investigated jointly with elements of EOSDIS (e.g., Pathfinder), in order to evaluate and further develop the ability to get important data in the hands of both scientists and land-managers quickly and easily.

Of particular interest is the development of new techniques that focus on the use of soon-to-be-available remotely sensed data. In particular, NASA is interested in exploring the potential applications of hyperspectral and very high resolution satellite data. The advent of the Lewis and Clark missions and the recent declassification of very high resolution imagery from defense satellites provide opportunities for exploratory research. In addition, NASA remains interested in technical research on, for example, automated change detection at the regional scale or improved classification algorithms, in order to improve the state of the art with respect to documenting land-cover and land-use change.

X. Links to other U.S. Agency Activities

Discussions have already been initiated across the agencies in the CENR. Interests of other agencies range from EPA's concerns about being able to account for changes in carbon flux on a country-by-country basis to concerns in the ecological research agencies for being able to map the occurrence of different land-cover types on the Earth's surface and being able to track changes in their extent, in order to understand patterns of biological diversity. These discussions will be broadened to include the practical concerns of the land management agencies of being able to standardize a system of vegetation classification. The NASA program can play a major role in understanding the relationship between changes in broad aspects of landscape structure and the ways in which these landscapes function. We envision providing a link between the largely remote-sensing based scientific community supported by NASA and the land managers of a variety of other Federal agencies through the collaborations produced in the CENR process. Collaboration with the NBS is already beginning to develop in the context of using NASA's specific expertise to help understand the consequences of land-use history on the current pattern of ecosystems and their functioning in the U.S.

Outside of the scientific arena, we also anticipate forming strong ties to U.S. agencies active in international development. Discussions with U.S. AID on a variety of projects have already begun, and there is some potential for stronger interactions in fields such as sustainable agriculture, agroforestry, and sustainable forest management in the developing world.

Another area of potentially strong interaction is with the U.S. Country studies program of DOE, EPA, and USAID, which helps developing countries develop methodologies for calculating greenhouse gas emissions, and studying climate change impacts, and possible mitigation strategies. Each of these requires both predictive ecosystem-level models, but also accurate assessments of land-cover and potential land-cover change.

XI. Links to International Activities

Links to the international science community will come largely through the activities of the IGBP and WCRP projects that focus either directly on land-use change, or on the processes that are affected as a result. IGBP is already working on a project to understand the technical consequences of combining data from the suite of multi-spectral, high spatial resolution remote sensing instruments that currently are in orbit: SPOT, Landsat MSS and TM, IRS, etc. In addition, IGBP-DIS is currently embarked on developing the technical and logistic requirements for acquiring and processing a global, high spatial resolution landcover data base, analogous to the 1-km AVHRR project (IGBP Report 20). IGBP-DIS is also engaged in the development of an improved global land cover data base at 1 km resolution. The new joint HDP/IGBP Core Project on Land-Use and Land-Cover Change is clearly of central importance, as are GCTE, IGAC, BAHC, GAIM, IGBP-DIS, possibly LOICZ, and certainly the WCRP GEWEX (GCIP and LBA) projects, and possibly GOALS.

The working relationship between the NASA Landsat Pathfinder and the ECE TREES project provides a good example of how international programs can be combined to provide improved global land cover assessments. Similarly the NASA Landsat Pathfinder program provides a complementary support activity to the UN/FAO Tropical Forest Assessment. Through this relationship links have been established with forest services of tropical countries. These kinds of mutually beneficial collaborations will be encouraged under the NASA land-use/land-cover change activity.

As in the U.S., links must be established with the international development community. There has already been some success within the Landsat Pathfinder in developing connections with the World Bank's Global Environmental Facility. Preliminary discussions with the UNDP have also been initiated through NASA Headquarters.

XII. Implementation Option

It is prudent to build on the investments that MTPE has made over the last several years.

Future Planning and Design Studies: *The primary effort in this area will be to conduct workshops and specialized, targeted analyses to coordinate appropriate activities within MTPE, among U.S. agencies, and integrate the MTPE efforts with those of the IGBP and WCRP.* We also anticipate supporting a small number of studies specifically targeted at questions of requirements for future satellite missions, both with outgrowths of existing technologies and for the development of new observational technologies. A specific effort will be initiated to scope the scientific and operational effort in land-use change necessary to take full advantage of the expected data streams from TRMM, Landsat-7, and EOS AM-1. Investigatory studies done jointly with other agencies will bring NASA's expertise to bear on problems of integrating land-use history with current ecological patterns and functioning within the U.S., and looking at the ecological issues associated with development and intensification of management in Central America.

Scheduling: *The first new solicitation was released in July 1996.* We should anticipate that the first round of projects selected will go through at least one three-year period of performance. During the first period of performance, the LBA campaign will begin. The focus of the land-cover/land-use change strategy will be to initiate pilot studies in each of the regions with emphasis in the first funding cycle on the Amazon Basin. At the end of the first three years, there will likely be a need to continue the Amazonian projects for some additional time. We should then anticipate a second RFP in approximately two years that would focus either on Southeast Asia or on southern Africa. A third RFP, to be scheduled about four years from now, would focus on the last tropical area or possibly on Russia and the countries of the FSU. It is possible that Russian and FSU work might be accelerated if there begins to be large-scale logging of the forests of Eastern Siberia, as the timber concessions start being utilized.

Through links to the Pathfinders and the land-cover projects, the first set of integrated reports of the consequences of human activities for the biosphere should be planned, written, and delivered shortly after the end of the first period of performance, i.e., during the major field activities of the LBA in 1998 (Fig. 6). The second set of integrated reports would follow in 2000, and would build on the routine delivery of ETM+ data from Landsat-7 and a variety of instruments from EOS AM-1 platform.

Through the series of solicitations anticipated now, and in conjunction with the base Terrestrial Ecology Program, the Tropospheric Chemistry Program, and others, we anticipate that major field campaigns, or smaller, more focused field studies, will be planned and implemented in these three primary regions early in the 21st century. By the year 2010, we should have completed major field activities in all three regions, and be positioned to make quantitative evaluations of the potential for sustainable land-use policies in the tropics and sub-tropics. This timing will be consistent with the major elements planned for the Earth Observing System and other international global change observing systems.

Section 2

Seasonal-to-Interannual Climate Variability and Prediction

EXECUTIVE SUMMARY

NASA's Office of Mission to Planet Earth (MTPE) has defined a focused research effort to observe, undertand, and predict climate variations that occur on time scales of seasons to a few years. This focused effort is important because variations in the upper ocean circulation and ocean surface temperatures, ocean color, sea ice, atmospheric circulation including the hydrologic cycle, atmospheric turbidity, and land surface conditions such as soil moisture and snow cover are hypothesized to be mutually interactive and to generate significant variations of climate on seasonal-to-interannual time scales, both globally and in specific regions. It is also believed that some part of this variability is predictable if relevant initial and boundary conditions are sufficiently well known. An improved understanding of the interactive climatic processes involved should lead to enhanced ability to predict significant variations in the system, including ones that are geographically specific, and to predict the consequences of these variations on ecosystems and on socioeconomic interests. Such an improved understanding and predictive capability is of potentially large socioeconomic benefit and thus warrants high research priority.

The major scientific questions that the seasonal-to interannual focused research effort will attempt to answer are the following:

- What is the detailed record of climate system variability on seasonal-interannual time scales for all relevant parameters, and what are the relationships among these parameters?
- What processes are important in causing variability of the system on these time scales, and how to they operate and interact to create observed variations?
- How can these processes be best represented in global and regional models that are intended to realistically simulate the complex behavior of the coupled climate system on seasonal-interannual time scales?
- To what extent are seasonal-interannual variations predictable, and what approaches using coupled system models along with other techniques will result in the most useful predictive capability for these variations and their effects on socioeconomic concerns?

In order to address these questions, the overall goal of the NASA/MTPE research focus on seasonal-to-interannual variability of the coupled ocean-atmosphere-land climate system is to:

- Develop remotely sensed observations and use them together with *in situ* observations to monitor, describe, and understand seasonal-to-interannual variability, with the aim of developing and improving capability to predict socio-economically important climatic events on these time scales.

Within this overall goal, there are four principal research objectives:

- Develop and use space-based and airborne observations of atmospheric temperature, winds, water vapor and precipitation, aerosol and cloud properties, sea surface temperature and topography, ocean color and biota, sea ice, soil moisture, land vegetation, snow cover, and radiative fluxes, in conjunction with *in situ* observations, to ascertain variability on seasonal-interannual time scales.

- Produce research quality climate data sets for seasonal-interannual applications by developing and improving methods for merging remotely sensed and *in situ* observational data and assimilating them with coupled Earth system models.

- Use observational and model-assimilated data sets to improve understanding of climate system processes and to improve coupled ocean-atmosphere-land-ice models that simulate or predict seasonal-interannual climate variations.

- Use MTPE observations, analyses, and models to characterize and predict seasonal-to- interannual variability, leading to an enhanced ability to reduce risk from floods, droughts, fires, and other natural hazards related to this variability.

Improved understanding and prediction of seasonal-to-interannual variability is a national priority of the U.S Global Change Research Program (USGCRP). The above MTPE objectives are consistent with this national priority, are supportive of the U.S. Global Ocean-Atmosphere-Land System (GOALS) national research program and the Climate Variability and Predictability (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX) international programs. They also contribute to the objectives of several other national and international research programs, sub-programs, and projects.

NASA/MTPE will design and implement contributions to seasonal-to-interannual research in areas where it has either demonstrated or potential capabilities and expertise. These include satellite- and aircraft-based observing systems, comprehensive data assimilation to include these observations, production of model-assimilated data sets and their distribution through the Earth Observing System Data and Information System (EOSDIS), field campaigns and other process and diagnostic studies that use MTPE observations and data sets, model development and application that capitalizes on the new information resulting from the data sets and the process and diagnostic studies, and application of all the above to the development of new ways to provide a basis for useful assessments of the impacts of seasonal-interannual variability on socioeconomic interests.

In carrying out its seasonal-to-interannual research activities, NASA/MTPE will coordinate its efforts to be complementary to those under way or planned at other federal agencies and at universities and other institutions. To the extent where it is possible and useful, MTPE will engage collaboratively with other research efforts. Activities will also be coordinated with other major research efforts within NASA, including other MTPE principal research foci (land-cover and -use, atmospheric ozone and other chemistry, long-term climate change, and natural hazards research), the MTPE Earth Observing System (EOS) and its interdisciplinary research program, the New Millenium technologies program, and the High Performance Computing and Communications (HPCC) program.

NASA/MTPE future research efforts will build on a strong foundation of on-going observational, process, diagnostic, modeling, and data analysis research activities. It is in both NASA's and the scientific community's interests that new spaced-based observing systems translate into significant advances in understanding, predicting, and assessing the impacts of seasonal-interannual variability. Key future observational activities include SeaWIFS, TRMM, NSCAT, Jason-1, and the EOS-AM and -PM instruments. These will greatly improve global coverage of several important climate system parameters. MTPE will continue working toward its 1998 implementation of a comprehensive data assimilation system that uses new as well as existing observations to produce high-quality model-assimilated data sets for climate research on seasonal-interannual as well as other time scales. MTPE will participate in and support GEWEX activites such as GCIP, ISLSCP, and GAME as well as similar GOALS activities as they are planned. A special effort will be made to increase the translation of research results from field campaigns, process studies, and diagnostic studies into useful parametric representations in numerical climate models.

Modeling research efforts will be directed toward development and application of coupled ocean-atmosphere-land system models that are capable of predicting climate variability on seasonal-interannual time scales and the regional impacts of such variability on concerns such as ecological balance, water supplies, agriculture, fisheries, etc. The results of these efforts should provide a basis for impact assessments and for natural hazards research. The potentially important value of satellite-based observations for seasonal-interannual assessment, and the conversion of these observations into useful information for assessments, will be the driving motivation for MTPE's seasonal-interannual assessment role.

An ability to monitor and predict significant variations of the climate system on seasonal-to-interannual time scales is of great importance for many socioeconomic interests in the United States and in other countries. The economic payoff of useful predictions of events like El Niño and its various regional effects or of droughts in the U.S. agricultural heartland should be immense. NASA/MTPE, in concert with other U.S. agencies and the broader scientific community, is well positioned to have an important role in research on seasonal-to-interannual climate variations that will lead to major improvements in monitoring and prediction and consequent large social and economic benefits.

◆ ◆ ◆

I. Introduction

Seasonal-to-interannual climate system variability manifests itself in several socioeconomically important ways. In the tropical Pacific basin, the occurrence every few years of El Niño has been linked not only to changes in marine life within the basin and to droughts and floods in land areas bordering the basin, but also to marked temperature and precipitation anomalies in more remote regions of the Earth, extratropics as well as tropics. Similar anomalous conditions (e.g., rainfall in eastern Asia, the African Sahel, and the Nordeste of Brazil) that persist for a season or more have been tentatively linked to the Quasi-Biennial Oscillation (QBO) or to variations of Atlantic ocean surface temperatures. Additionally, there are other persistent anomalous regional temperature and precipitation events, such as the hot, dry summer of 1988 or the unusually wet one of 1993 in the central United States, that were not as clearly linked to major global climate signals but instead may depend at least partly on antecedent soil moisture conditions. Early season snow cover may affect cold season temperatures in some areas, although cause and effect has not been clearly demonstrated. All of these anomalous conditions are associated with large socioeconomic costs, often totaling in the billions of dollars. An ability to accurately monitor these conditions and especially to understand and predict their evolution will clearly be of great economic value.

Both the understanding and prediction of climate variability on seasonal-to-interannual time scales require accurate measurements of global atmospheric, upper ocean, and land surface conditions as well as improved models to simulate their mutual evolution. The 15 years of observations expected from the Earth Observing System (EOS) and other Earth probes of NASA's Mission to Planet Earth (MTPE) program are well suited for a research focus on seasonal-to-interannual time scales. The planned program of space-based observations should provide several independent measurements of significant climate system variability in addition to those available from *in situ* observations. In association with other concerned agencies and organizations, NASA/MTPE is positioned to use all these observations in the context of a major focused research effort that builds upon past scientific accomplishments and achieves significant improvements in understanding and predicting seasonal-interannual variability.

The overall goal of the NASA/MTPE research focus on seasonal-to-interannual variability of the coupled ocean-atmosphere-land climate system is to:

> *develop remotely sensed observations and use them together with in situ observations to monitor, describe, and understand seasonal-to-interannual variability, with the aim of developing and improving capability to predict socio-economically important climatic events on these time scales*.

Within this overall goal, there are four principal research objectives:

- ◆ Develop and use space-based and airborne observations of atmospheric temperature, winds, water vapor and precipitation, aerosol and cloud properties, sea surface temperature and topography, ocean color and biota, sea ice, soil moisture, land vegetation, snow cover, and radiative fluxes, in conjunction with *in situ* observations, to ascertain variability on seasonal-interannual time scales.

- ◆ Produce research quality climate data sets for seasonal-interannual applications by developing and improving methods for merging remotely sensed and *in situ* observational data and assimilating them with coupled Earth system models.

- ◆ Use observational and model-assimilated data sets to improve understanding of climate system processes and to improve coupled ocean-atmosphere-land-ice models that simulate or predict seasonal-interannual climate variations.

- ◆ Use MTPE observations, analyses, and models to characterize and predict seasonal-to- interannual variability, leading to an enhanced ability to reduce risk from floods, droughts, fires, and other natural hazards related to this variability.

The central hypothesis of the MTPE focused research effort is that variations in the upper ocean circulation and ocean surface temperatures, ocean color, sea ice, atmospheric circulation including the hydrologic cycle, and land surface conditions such as soil moisture and snow cover are mutually interactive and can generate significant variations of climate on seasonal-to-interannual time scales, both globally and in specific regions. A corollary is that some part of this variability may be predictable if relevant initial and boundary conditions are sufficiently well known. Also, major volcanic eruptions modulate radiational balance and consequently affect temperature (directly) and other climatic parameters (indirectly) for periods up to a few years. An improved understanding of the interactive climatic processes involved should lead to enhanced ability to predict significant variations in the system, including ones that are geographically specific, and to predict the consequences of these variations on ecosystems and on socioeconomic interests.

Improved understanding and prediction of seasonal-to-interannual variability is a national priority of the U.S. Global Change Research Program (USGCRP). The above MTPE objectives are consistent with this national priority and closely parallel the seasonal-interannual research objectives of USGCRP as given in Our Changing Planet, FY 1996. The above objectives are supportive of the U.S. Global Ocean-Atmosphere-Land System (U.S. GOALS) national research program, the seasonal-interannual component of the Climate Variability and Predictability (CLIVAR) international program, and the international

Global Energy and Water Cycle Experiment (GEWEX), especially the GEWEX Continental-Scale International Project (GCIP).

This document is intended to provide an overall seasonal-interannual variability research strategy and identify the role that NASA, in concert with other U.S. agencies, national and international programs, and the scientific community, will have in this overall effort. As a strategy document, it is not intended to provide detailed plans for implementation of specific research projects. NASA currently has many on-going activities that contribute to seasonal-interannual research; some of these are identified below. This document will serve as a guiding framework for development of more detailed plans for other activities that are also needed.

II. Background

NASA/MTPE has been a U.S. participant in the international Tropical Ocean-Global Atmosphere (TOGA) and Global Energy and Water-Cycle Experiment (GEWEX) research programs, in collaboration with NOAA, NSF, and ONR. TOGA has focused on understanding and predicting the El Nino-Southern Oscillation (ENSO) climatic signal, long recognized as being the most prominent interannual tropical variation and one with global consequences. TOGA has successfully mounted a field campaign (COARE), greatly improved in situ measurements in the tropical Pacific basin (e.g., the TAO array), used remotely sensed data to monitor critical parameters (e.g., sea surface temperature and topography; deep atmospheric convection as determined from outward long-wave radiation measurements), and initiated experimental predictions of ENSO fluctuations. MTPE scientists have participated in the TOGA Program on Prediction, involving collaborations with NOAA and with other institutions. For example. a recent collaboration of GSFC, Lamont Doherty Earth Laboratory (LDEO), and University of Rhode Island scientists, using a procedure that combines a simplified coupled ocean-atmosphere model with assimilation of surface winds has resulted in a potential ability to predict ENSO conditions more than a year in advance (Fig. 2-1).

The ten-year TOGA program has been completed and has generally achieved its objectives. Another national program, GOALS, has been developed to both continue and expand research on seasonal-to-interannual variability. GOALS is a U.S. contribution to the international CLIVAR program and has the expanded scope of understanding and predicting connections between the tropical Pacific ENSO signal and climatic variations in other parts of the world as well as causes and predictability of climate variations not directly attributable to ENSO. NASA/MTPE is positioned to play a significant role, in partnership with other agencies, in research directed toward the broader objectives of GOALS, in terms of satellite-based observational capabilities, field campaigns, process studies, modeling, data assimilation, prediction, and assessments.

NASA helped initiate and continues support of the GEWEX project, which is focused on integration of many current and planned (e.g., EOS) satellite observations into global and regional data sets useful for defining the “fast” climate processes (e.g., atmosphere-land interactions in the context of the hydrologic cycle). This information is needed to extend predictive capability to seasons and longer. NASA/MTPE has been a participant in many of the continuing GEWEX activities that contribute to development of seasonal-interannual predictive capabilities. These activities include the International Satellite Cloud Climatology Project (ISCCP), the International Satellite Land Surface Climatology Program (ISLSCP), the Global Precipitation Climatology Project (GPCP), the Surface Radiation Budget (SRB) activity, and the GEWEX Water Vapor Project (GVaP). Other relevant activities include regional campaigns such as the GEWEX Continental-Scale International Project (GCIP), in which NASA will have an important role in terms of observing the hydrologic cycle on

Predictive Skill Measured by Niño-3 SST Anomaly

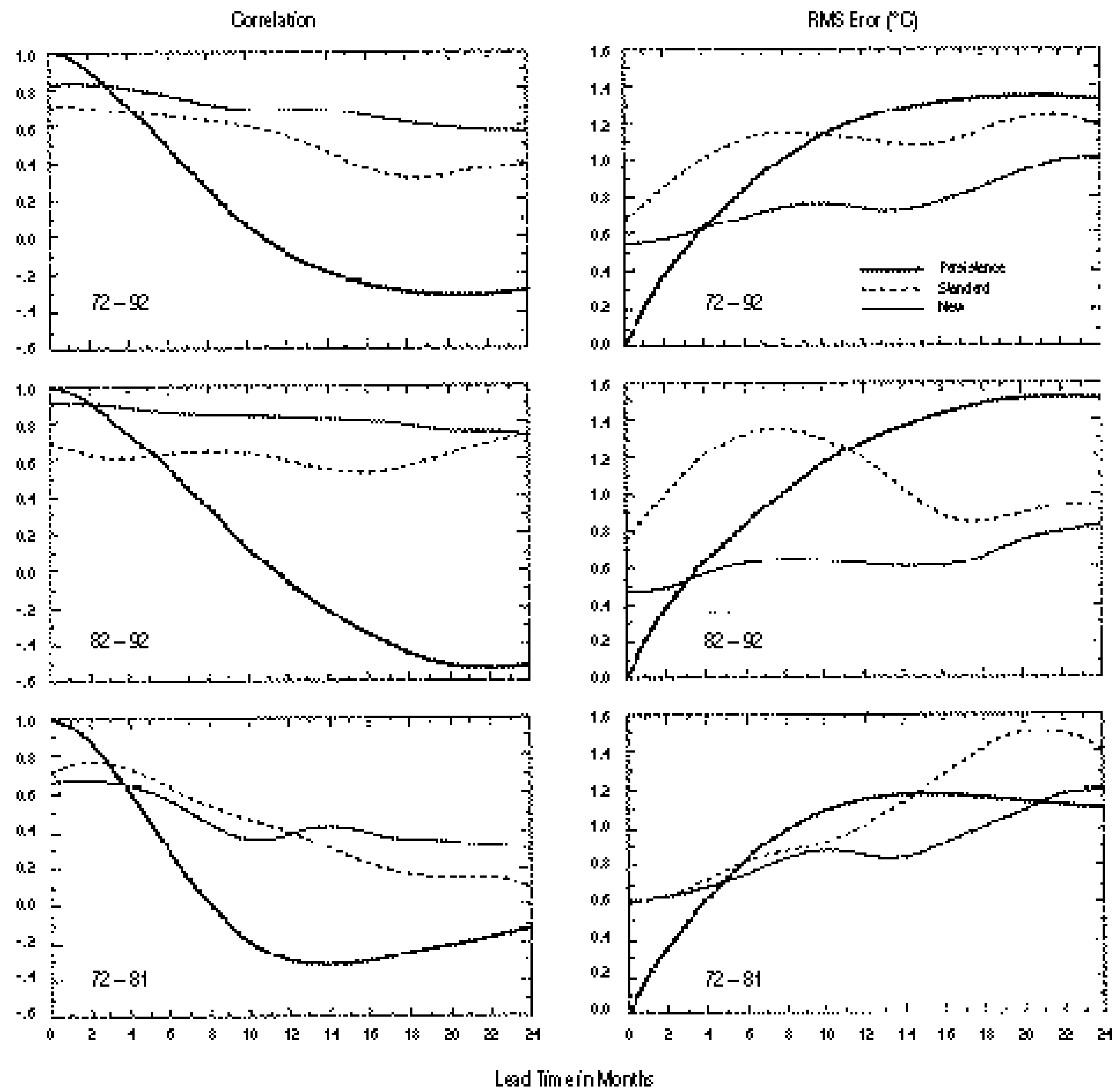


Fig2-1

seasonal-interannual time scales, and model development studies such as the GEWEX Cloud System Study (GCSS) and the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS).

These GEWEX activities are important in providing data sets both for evaluating the realism of climate models and for improving the representation of atmospheric and land surface processes in models. The result should be more accurate predictions of regional flood and drought conditions on seasonal and longer time scales as well as improved predictions of continental-scale circulations, such as Asian monsoon onset, intensity, and retreat, that affect regional climate.

Although their focus is primarily on longer time scales, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS) also contribute to a better understanding of the global climate and provide a context for seasonal-interannual variability as related to long-term trends. In particular, JGOFS is focused on how ocean biogeochemical processes influence and respond to climate changes on all time scales. NASA is a participant in these international programs.

In addition, although occurrences are not predictable, the effects of major volcanic eruptions, once they do occur, on the climate system are predictable, at least on a global or hemispheric basis. NASA recently launched an initiative to study all aspects of stratospheric aerosols from volcanoes, including chemical transformations, affect on radiation balance, and, using global models, their affect on climate. Results of some of these studies showed that the Mt. Pinatubo eruption of 1991 caused a global mean temperature increase of about 2°C in the stratosphere and a decrease of about 0.5°C in the troposphere and at the surface for at least a year. Furthermore, a global climate system model (GISS AGCM) was able to predict these aerosol-induced temperature anomalies approximately a year in advance from initial aerosol cloud information. Although these anomalies may seem small compared to anomalies attributed to major El Niño events, they nevertheless contribute to seasonal-interannual variability on a global or hemispheric scale. Further research on volcanic aerosols and their climatic consequences is continuing. (Similar research proceeds on tropospheric aerosols from sulfates and bio-mass burning, but significant effects on seasonal-interannual variability have not been shown, although they have significance for longer-term trends.)

All of these studies will require the use of remotely sensed observations, in conjunction with *in situ* measurements, of key oceanic, land surface, and atmospheric parameters. Intensive field campaigns, carefully designed studies of relevant climatic processes, and climate system simulations with coupled regional and global models will also be required to achieve the objectives of GOALS and GEWEX and are an important national priority of the USGCRP. Together with other agencies, MTPE is formulating strategies for enhanced participation in each of these areas.

Significant recent research accomplishments for seasonal-interannual time scales that were supported by NASA/MTPE include the following:

- Extended the potential lead-time of skillful El Niño forecasts to as much as 20 months using an innovative procedure that explicitly represents air-sea interaction in model initialization. (Supported jointly with NOAA).

- Developed a coupled ocean-atmosphere-land model that simulates, without ocean-atmosphere flux correc-

Fig. 2-1(left): Correlations and rms errors between predicted and observed Niño-3 SST anomalies for three time periods. In each panel, results from the standard Cane-Zebiak model, the new model, and persistence forecasts are shown for comparison. Persistence forecasts are obtained by assuming initial SST anomalies remain constant (from Chen, Zebiak, Busalacchi, and Cane: An Improved Procedure for *El Niño* Forecasting.)

tions, the basic coupled climate state, the seasonal cycle, and ENSO variability. The land surface model component uses a novel mosaic approach to represent the effects of heterogeneous land cover.

- ◆ Produced radar altimeter (TOPEX/Poseidon) measurements that provide instantaneous sea surface topography with an accuracy of 3–4 cm and monthly mean topography with an accuracy of less than 2 cm. This accuracy has permitted the tracking of ENSO-generated Rossby waves in the Pacific Basin as well as regional and global mean sea level changes in response to global temperature changes.

- ◆ Used satellite outgoing long-wave radiance (OLR) imagery to define the frequency, propagation, longevity, and other characteristics of Madden-Julian oscillations in the tropical oceanic atmosphere and to study their teleconnections to seasonal anomalies in other geographic regions.

- ◆ Confirmed the existence of quasi-biennial variability of the East Asian monsoon and linked this variability to quasi-biennial variations in other parts of the tropical climate system, with the possibility of improving both monsoon and ENSO predictability.

- ◆ Demonstrated that continental interior summer rainfall anomalies such as the 1993 anomaly in the central USA are predictable at least a month in advance when soil wetness and other land surface and atmospheric boundary layer processes are represented realistically in an interactive model.

- ◆ Developed a cloud ensemble model nested in a regional model and used the combined system to understand the physics and dynamice of super cloud clusters in the tropics and their impact on larger scale climate processes.

- ◆ Provided the first detailed in situ observations of precipitation systems in the WesternPacific using shipborne weather radars during TOGA/COARE. These observations have been used to detect low-frequency modulation of the diurnal rainfall cycle and to evaluate the performance of rainfall estimation algorithms being developed for TRMM and the GEWEX Global Precipitation Climatology Project (GPCP).

- ◆ Developed the world's first multi-year assimilated global atmospheric data set (1985–89, being extended to 1979–94) that employs a uniform, non-varying assimilation system. This data set is particularly suitable for studying seasonal-interannual climate variations since artificial signals from system changes that are typical of operational systems have been eliminated.

III. Program Elements: Current Status and Outlook

There are five major elements of MTPE's focused research effort in seasonal-to-interannual climate variability: observations, data assimilation, process and diagnostic studies, modeling, and assessments. Each of these is discussed below in terms of current activities and future needs.

Observations

Observations are needed to (a) provide monitoring of the climate system in order to assess variability on a global scale in near-real-time, (b) improve understanding of key climate system processes, leading to improved parameterizations of these processes in global models, and (c) initialize and verify models of the coupled climate system for predictions and assessments.

Remote sensing has a critical role in providing global data sets for each of these purposes. TOPEX/Poseidon launched in 1992 is providing ocean surface topography measurements, with a root-mean-square error of about 4 cm, that are capable of detecting and monitoring ENSO-related signals in the Pacific basin. Successful launch of currently planned earth-observing satellites (ADEOS, TRMM, EOS-AM and -PM, and the TOPEX/Poseidon follow-on (Jason-1)) will greatly increase the amount and quality of pertinent remotely sensed data. Additionally, existing data sets (e.g., TOVS Pathfinder, new altimeter Pathfinder) can provide enhanced information through reprocessing and reanalysis; this is important for establishing the historical record of variability for research studies.

MTPE will provide vital observations for the ocean component of the climate system, including surface wind stress (SSM/I, NSCAT), surface topography (TOPEX/Poseidon), and ocean color (SeaWIFS). These, together with sea-surface temperatures (AVHRR, ATSR, MODIS, OCTS) provided by other agencies and combined with *in situ* measurements of surface and sub-surface current, upper-ocean thermal structure, and upper ocean salinity will provide the observational basis for upper ocean dynamics and its interaction with the atmosphere. It is important to measure or otherwise determine the amount of insolation at the sea surface both in clear and cloudy conditions. The penetration of visible solar radiation to subsurface depths has a potentially significant (0.5°C) effect on the evolution of SSTs in equatorial oceans, requiring both satellite and in situ measurements of ocean color due to biota concentration. It is also important to measure oceanic rainfall that affects sea surface temperature and salinity. Sea ice extent and continuity need to be observed using passive microwave sensors in conjunction with in situ calibration.

Current observations of the atmosphere will be greatly augmented by new instruments on the EOS-AM and -PM platforms and on other Earth probes. Rainfall, cloud, and radiation measurements provided by the Tropical Rainfall Measurement Mission (TRMM, launch scheduled for 1997) will be of particular importance for improving understanding of tropical and sub-tropical precipitation processes and variability and their linkage, through the release of latent heat to the upper troposphere and resultant dynamic perturbations, to climate anomalies in other parts of the world. Concentrations of stratospheric sulfate aerosols have been quantified by the SAGE I and II instruments (also to some extent by AVHRR, UARS, and TOMS instrumental measurements); these measurements will be continued into the next decade by the launch of SAGE III in 1998. Follow-on launches to TRMM, the initial EOS-AM and -PM instruments, TOPEX/Poseidon, and other Earth observing systems will also be needed for continued advances in understanding and prediction of seasonal-interannual variability .

On land, seasonal and interannual variations in global snow cover and liquid equivalent can be estimated using SSM/I data. Variations in soil moisture can be measured on larger scales using both longwave and microwave remote sensing, with *in situ* observations providing interpretative calibration, and smaller scale analysis can be provided through GEWEX/ISLSCP field measurements. In particular, the ISLSCP Soil Wetness Project is designed to produce global data sets of soil wetness that are necessary for specifying initial and boundary conditions as well for evaluating predictive global models. The FIFE, BOREAS, and LBA field experiments have and will provide useful "ground truth" information for calibration of satellite observations as well as data bases for land surface process studies. *In situ* data from GCIP will provide similar capabilities. Seasonal and interannual variability of vegetative transpiration relative to biomass production is being quantified with remotely sensed Normalized Difference Vegetation Index (NDVI) data as an important step toward quantifying evapotranspiration globally.

Since NASA has the primary research and development responsibility and NOAA the operational responsibility for space-based observations, it is essential that these agencies work together in complementary fashion to develop the best possible global observing system, including a full suite of in situ observations, for both research and operational monitoring and prediction purposes. Increased observational capability is needed to make progress in understanding, modeling, and prediction. Also needed is merging of differently observed data concerned with the same variable.

A management framework is needed for developing a coordinated system of both existing and new satellite-based and in situ observations. This is the rationale for development of an Integrated Global Observing Strategy (IGOS) that will help fulfill the observational needs of programs such as CLIVAR/GOALS and GEWEX. Internationally, the emerging Global Climate Observing System (GCOS) will coordinate observing system requirements and provide guidance for the development of future global boserving systems.

DATA ASSIMILATION

Space-based observations by themselves are of limited value unless they can be placed in context with other data and with what we already know about the mechanics of the coupled climate system. Data assimilation provides a dynamical, physical, and chemical framework for combining a large variety of satellite and *in situ* observations into globally consistent data sets suitable for climate monitoring and research.

By optimally combining observed data with predicted values provided by a cycling climate system model, data assimilation provides an estimate of the state of the climate system and how it evolves in time that is more complete and accurate than either the observations or the model can provide alone. Additionally, optimum observational requirements can be developed and model development can be accelerated and made more quantitative through the systematic confrontation between model and observations that occurs in data assimilation.

The NASA/GSFC Data Assimilation Office (DAO) will routinely provide a hierarchy of model-assimilated data sets of atmospheric, land surface, and ocean surface products, starting at the opening of the EOS era in 1998. Prototypes of these data sets are currently available through the data interface of the GSFC Distributed Active Archive Center (DAAC). The DAO will provide near-real-time data sets for use by instrument teams and time-critical science applications. Delayed analyses will use appropriate data from MTPE platforms along with advanced data assimilation techniques to focus on analyses of specific processes and development of model parameterizations. Decadal and longer-period retrospective analyses will be produced specifically for climate applications such as quantifying natural climate variability, understanding key climatic processes, and developing more realistic climate models. Unique aspects of the DAO assimilation effort include a strong emphasis on early incorporation of new kinds of advanced satellite observations as they become available and an emphasis on production of research quality model-assimilated data sets retrospectively using a system that is optimized for this purpose rather than for operational weather prediction.

Currently, the DAO is extending an already-produced 5-year retrospective analysis of atmospheric data (1985–1989) to 16 years (1979–1994). This data set serves as a benchmark for future assimilation system development and as a source of useful information for seasonal-interannual research by scientists, who also provide feedback on data set quality to the DAO. Sufficiently long retrospective analyses provide a consistent treatment of past observed data for the study of interannual variability such as that associated with ENSO (Figs. 2-2 and 2-3, which contrast an *El Niño* year, 1987, with a “La Niña” year, 1988). The DAO has also produced several specialized model-assimilated data sets for the study of tropospheric and stratospheric circulation and chemistry, especially that associated with the QBO. These data sets

Fig. 2-2 (right): Precipitation (shaded), low-level wind speed at 850 mb (contours), and vertically integrated moisture transport (vectors) for (a) July 1987 and (b) July 1988 from the GEOS-1 assimilation. Contour interval is 2 m/sec. Units are mm/day for precipitation, m/sec for wind speed, and g/Kg m/sec for moisture transport. Contours less than 8 m/sec are not shown.

GEOS Analysis

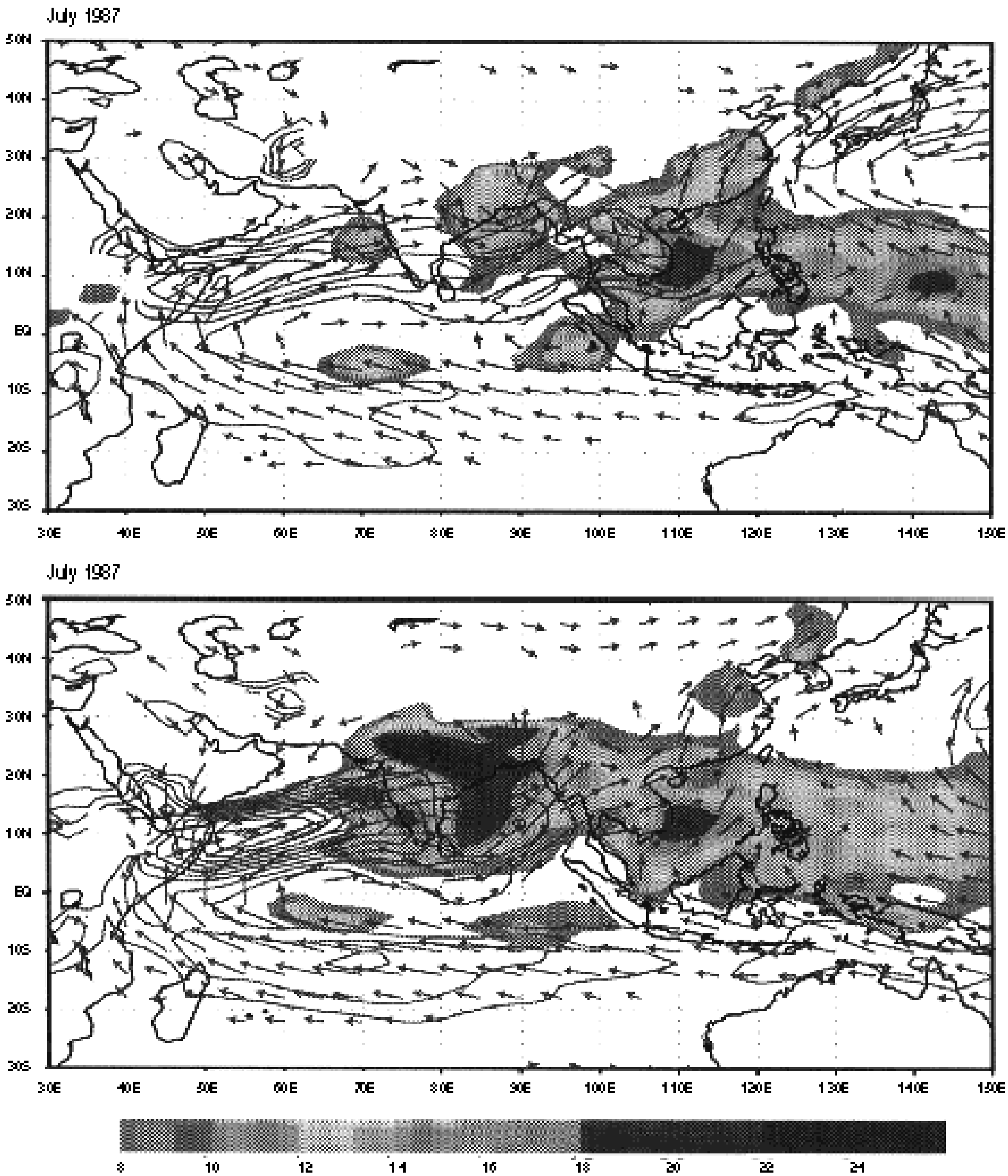


Fig2-2

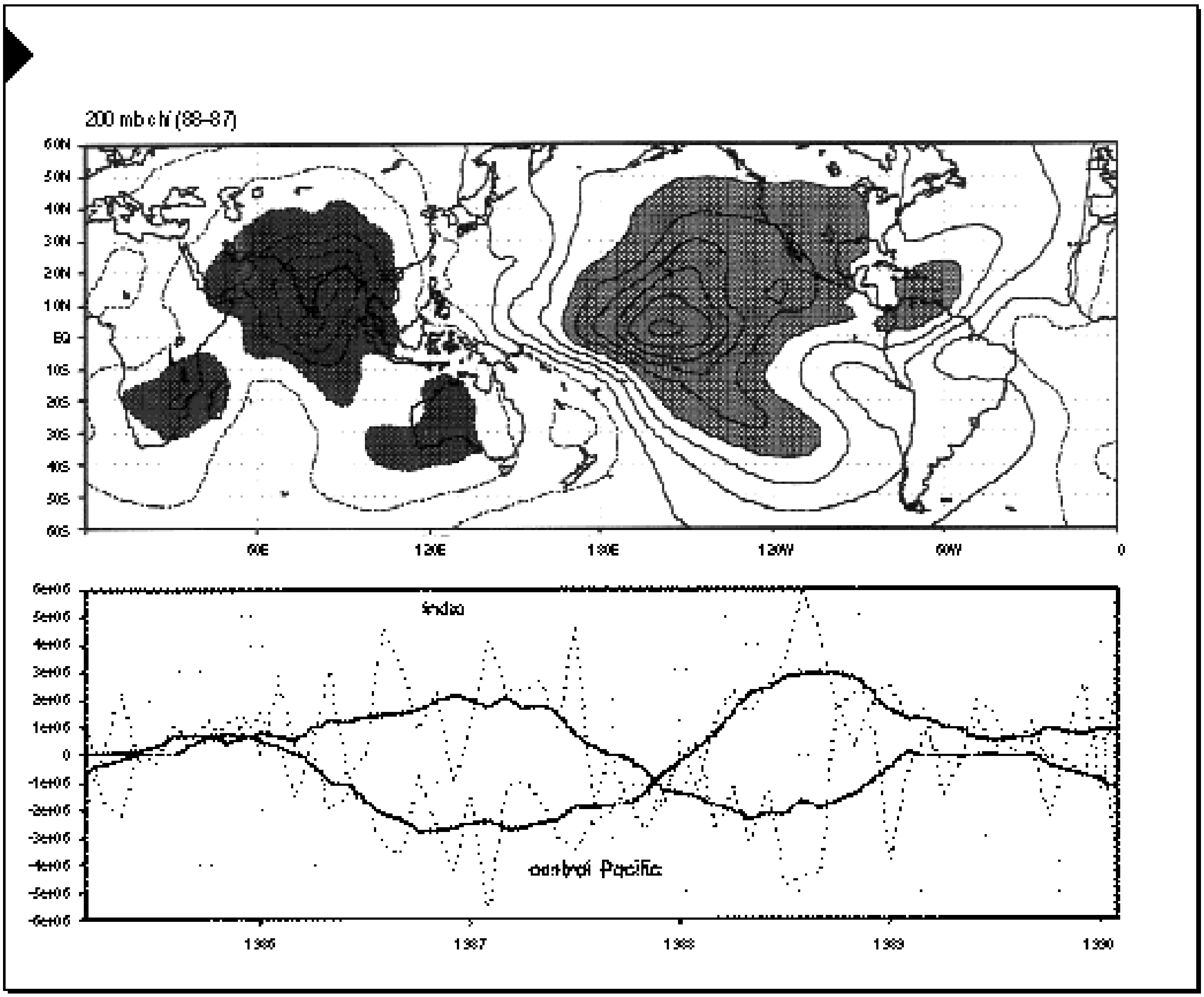


Fig2-3

Fig. 2-3 (above): Top Panel– Difference in atmospheric mass divergence at 200 mb *between an* El Niño *year (1987) and a non-*El Niño *year (1988). Solid contours indicate increased convergence in 1988, and dashed lines indicate increased divergence in 1988, compared to 1987.*

Bottom Panel– Monthly values and nine-month running means of mass convergence at a grid point over India compared with a grid point in the central pacific. Units are m/sec/m.

provide a basis for understanding climate-chemistry coupling processes.

The ocean and, to a lesser extent, land surfaces have dominant roles in determining coupled climate system memory on seasonal-interannual scales. More comprehensive land and upper-ocean data assimilation is needed, with the ultimate goal of coupled system data assimilation using coupled system models. Pilot studies for assimilation of ocean topography (using TOPEX-Poseidon observations) and ocean surface wind stress (using SSM/I and ERS-1 data) and of surface soil moisture have been initiated at GSFC, JPL, and elsewhere. It is important that these and similar data assimilation activities be expanded and integrated as rapidly as possible. Further progress in seasonal-to-interannual prediction will depend critically on the existence of comprehensive coupled system data assimilation, both for verifying the performance of predictive models and for providing complete and accurate initial conditions for actual predictions. Also needed is a capability to perform higher resolution regional data assimilation for specific areas within the context of global assimilation.

PROCESS AND DIAGNOSTIC STUDIES

The objective of the focused activity's process research is to improve understanding of climatically important processes that currently are poorly represented either directly, or indirectly through parameterizations, in global models used to simulate and predict seasonal-to-interannual climate variations. Process studies involving field experiments will provide research-quality in situ data sets for detailed diagnosis of deficiencies in methodologies used to process remotely sensed data and for improvement of parameterization schemes used in models. For example, FIRE and ISLSCP field experiments have resulted in process research useful for improvement of cloud and land surface parameterizations, and TOGA/COARE data are being used to quantify momentum, heat, and moisture fluxes between the tropical ocean and atmosphere in the Western Pacific warm pool, a key ENSO region.

Additionally, related diagnostic studies are needed to examine the effects of processes on larger scales, including global scales. These studies look at the dependence of larger-scale climate features on one or more key climatic processes and their parameterized or other representation in climate system models. In the following two lists, many of the studies identified as needed include both a process study component (in the sense described above) and a diagnostic component. Others are primarily either process or diagnostic studies.

Studies are needed to provide increased understanding in the following topical areas, some of which are overlapping:

- Structure and dynamics of the annual cycle of the coupled climate system, especially its large spatial variability globally.
- Nature of processes controlling interannual climate variability and its relationship to the annual cycle.
- Role of varying conditions at the surface (e.g., SSTs, sea ice, sea surface chlorophyll concentration, soil moisture, and snow cover) in determining seasonal and interannual variations of the global atmosphere.
- Factors affecting low-level moisture convergence and release of latent heat in the tropical atmosphere and its effect on global atmospheric circulation.
- Role of tropical SSTs in perturbing the extratropical atmosphere and thereby generating both extratropical SST anomalies and anomalous climatic conditions over land, with possible interactions between these anomalies.
- Role of synoptic features (e.g., Madden-Julian oscillations) in the tropics and their role in seasonal-interannual variability.
- Quantitative estimate of the predictability of extratropical seasonal anomalies of circulation and rainfall.
- Simulation and prediction of regional climate by coupling global climate models and high resolution regional models.
- Role of soil moisture, vegetative, and snow cover anomalies in climate variability and persistence, especially in continental interiors.
- Factors affecting latitudinal and temporal distribution of stratospheric aerosols from volcanoes, and their conse-

quent effects on latitudinal and temporal radiational balance.

- Ecosystem responses to changes in physical climate, and resulting effects on agricultural and fisheries productivity.
- Role of marine ecosystems in climate variability (e.g., through changes in ocean transparancy and production of di-methyl sulfides).
- Factors affecting the variability of carbon cycling in the upper ocean on seasonal-interannual time scales.

A partial list of more specific studies that are needed include:

- Moist atmospheric processes using sounding data, assimilated data, and convective cloud ensemble models.
- Oceanic heat balance in regions where models have difficulty simulating SSTs, such as regions of equatorial upwelling.
- Reflection of oceanic Rossby waves in the western Pacific and implications for ENSO.
- Improved parameterization of boundary layer winds in AGCMs.
- Role of stratus cloud decks in oceanic heat balance.
- Roles of the western and eastern boundary currents in oceanic heat balance and transport of heat to higher latitudes.
- Detailed structure of atmospheric and oceanic surface anomalies associated with ENSO using ERBE and ISCCP data and DAO reanalyses.
- Atmosphere-ocean interaction associated with 40–60 days Madden-Julian disturbances.
- Role of convective cloud processes in generating westerly wind bursts in the tropics and their relationship to Madden-Julian disturbances.
- Regional water and energy cycle studies in conjunction with international field experiments in differing climatic regimes, e.g., Mississippi Basin (GCIP), Amazon (LBA), East Asia (GAME), and South China Sea/maritime continent (SCSMEX).
- Relative roles of SSTs and land surface conditions in determining location and strength of monsoon heat sources and sinks and resultant dynamical response.
- Mechanism for monsoon onset and northward migration, and relationship to subsequent development of seasonal monsoon.
- Impact of monsoon on global climate variability.
- Monsoon-ENSO interaction and its possible role in predictability of the coupled ocean-atmosphere-land system in the tropics.
- Role of coastal currents and trapped Kelvin waves in causing ENSO effects along coasts of California, Mexico, and Chile.
- Origin of subpolar salinity fluxes and their role in modulating air-sea energy fluxes.
- Causes of interannual variations in sea-ice extent and relationship to atmospheric variability.
- Parameterization of land surface water and energy balance and fluxes for climate system models using field data (ISLSCP/GCIP initiative).
- Improved understanding of climate teleconnections between higher latitudes and the tropics.
- Impact of water composition and transparency on upper-ocean dynamics.
- Impact of changes in ocean ecosystem productivity on ocean transparency.

NASA/MTPE's tasks in these studies are to identify the role of space-based and airborne observing systems in providing essential data, to apply unique capabilities and expertise to optimize use of such data in concert with other types of data, to plan and carry out field experiments, special analyses, and in-depth studies in collaboration with other agencies and organizations where appropriate, and, most importantly, to translate the results of such studies into improvements in understanding, modeling, and predicting important aspects of seasonal-interannual variability. NASA is currently supporting research efforts in several of the listed specific studies.

Modeling and Prediction

The objective of the seasonal-to-interannual modeling and prediction element is to combine the use of observed data, the results of process studies, and physical-dynamical understanding to develop or improve global-scale coupled models of the climate system and use them to simulate and predict seasonal-to-interannual climate variations. Clearly, modeling has a central role; it provides the essential linkage between observations and understanding on the one hand and simulations and predictions useful for climate assessment purposes on the other. Since the climate system involves oceanic, atmospheric, land, and cryospheric components, coupled models also serve as the mechanism to represent the complex interactions among these components that cause variability of the climate system to occur.

Models also have a useful role in evaluating the quality and impact of observed data and in helping to identify observational needs, especially in terms of needed observational density and quality (e.g., Observing System Simulation Experiments). Models play a key role in modern four-dimensional dynamic data assimilation, where the scientific understanding implicit in models is optimally combined with observational data. Conversely, data assimilation provides a basis for model verification and model improvements. This synergism between data assimilation and model development is an important reason why these activities should be carried out in close coordination.

Although development and use of models for seasonal-interannual prediction have much in common with their development and use for longer-term climate change issues, there are enough significant differences to warrant development of a separate climate system model, or of a specialized version of a more comprehensive Earth system model, for seasonal-to-interannual applications. On these time scales, only the upper few hundred meters of ocean interact significantly with the atmosphere; thus a simplified representation of the deeper ocean can be used. The radiational effects of stratospheric aerosols can be approximately represented by a re-partitioning of incoming solar radiation between stratosphere and troposphere. On the other hand, initial conditions of upper ocean, sea-ice, and land surface properties must be specified very accurately since they have the potential to persist for a season or longer. Correct representation of the hydrologic cycle, especially land hydrology, is important on these time scales. Also, the scale-interaction that takes place between smaller and larger spatial and temporal scales must be represented either explicitly or through use of parameterized representations.

Effort should be directed toward improving the component ocean, sea-ice, land surface, and atmospheric model representations in coupled model systems. Ocean models need improved vertical mixing parameterizations, improved ability to simulate SSTs, improved parameterizations of poleward heat flux by sub-grid eddies, coupling with sea-ice models, and incorporation of biogeochemical processes that affect interannual fluctuations in carbon dioxide. Sea-ice models need improved representation of wind stress effects, heat flux through leads, and thickness growth and decay. Land surface modeling efforts need to focus on more realistic land hydrology representation and on ecosystem feedback to the atmosphere. For example, recent PILPS intercomparisons have demonstrated that land surface model behavior is very sensitive to how riverine runoff and subsurface flow are represented. Atmospheric models also have significant deficiencies (e.g., accurate quantifications of cloud-radiative feedback, atmospheric boundary layer fluxes, and deep convective transport of water vapor) which require continued research effort. It is critical for coupling with ocean and land surface models that atmospheric models should be able to realistically represent the atmospheric hydrologic cycle, including cloud-radiative dynamic feedback processes. Development of prognostic cloud water schemes, with improved microphysics-based radiative parameterizations, is a high priority modeling research objective.

Model performance must be carefully evaluated. In addition to basic simulations of mean climate state and the annual cycle, evaluation is primarily through simulations of past climate system evolution and comparison with available observational data or, more comprehensively, with model-assimilated data sets. Reasonably long, accurate, and complete records of key climate variables are needed for this purpose. Remotely sensed data has a key role in these evaluations because of its global coverage and, for some data streams, its continuity (given temporal overlap between successive sensors). Ability to simulate the past evolution of the climate system with a minimum of parametric tuning, intermedia flux adjustment, or bias correction should be the goal of model evaluation, leading to increased confidence in the reliability of the model to predict future climate system evolution with reasonable accuracy.

It is desirable to evaluate parameterization schemes in models in conjunction with appropriate field campaigns (e.g., LBA and GCIP for parameterization of land surface variables). Development of variable resolution models and techniques for nesting regional models in global models are useful for this purpose. Currently, NASA/MTPE supports both regional and global modeling. These modeling efforts should be coordinated and should use the abundant *in situ* and remotely sensed data from large-scale field experiments as test beds for new parameterizations and other numerical schemes. The results of process modeling based on field experiments and other data should translate into improved parameterizations for larger scale models.

Intercomparisons of the climate simulations of models that have been developed comparatively independently (e.g., AMIP, PILPS, SMIP) are also useful for evaluating model performance relative to state-of-the-art, both overall and for specific climatic features. These intercomparison activities have brought together a large number of modelers who have exchanged information and ideas on model development and application. NASA-supported modelers have participated and benefited from these intercomparisons. The AMIP intercomparison has resulted in implementation of new physical parameterizations in the GLA GCM, resulting in improved simulation of the global and regional hydrologic cycle. Under the auspices of the WCRP, an AMIP-II project is being planned. AMIP-II aims at a 15-year intercomparison of state-of-the-art atmospheric models forced by identical SST and sea-ice conditions. This activity should complement several modeling activities currently supported by NASA/MTPE. The PILPS intercomparison has resulted in an improved land surface component in the GSFCcoupled model. NASA is also supporting a Seasonal Model Intercomparison Project (SMIP) that is coordinated by the Center for Ocean-Land-Atmosphere (COLA) as part of CLIVAR/NEG. In this project, several NASA supported modeling groups are participating in ensemble seasonal predictability experiments.

ASSESSMENTS

The objective of the assessment element of the seasonal-to-interannual research focus is to develop, for this time scale, procedures for delivering useful information on current variations and useful predictive estimates of future variations in the climate system, with special attention given to those that have significant socioeconomic impacts. The primary information sources for assessments are analyses of observational data for monitoring purposes and model simulations for predictive purposes. In each case, it is very important that estimates of accuracy or reliability be provided as well. The assessments must be sufficiently specific in content, as well as expressed in terms that permit their use in determining likely impacts and in formulating response strategies.

Model-assimilated data sets with time continuity are ideally suited for monitoring current climatic variations such as those associated with ENSO. Also useful is calibrated satellite imagery, such as the Normalized Difference Vegetation Index (NDVI), remote measurements of SST and OLR, and ocean surface topography. In order to assess the likely socioeconomic impact of a significant ENSO or other climate system fluctuation, it is necessary to evaluate it in the contexts of mean, undisturbed conditions and of previous historical fluctuations. Periodic reanalyses of the global observational data base using a uniform assimilation methodology, such as that employed by the GSFC/DAO and by NOAA/NCEP, will provide the best possible historical context for both monitoring and prediction.

Predictive assessments need to be performed with models and empirical tools that have been carefully tested in experimental mode. Among the predictive assessments, with lead times of a season to a year or more, which are now feasible or have the potential to become feasible within the next several years are ones for ENSO and its global consequences, the Asian monsoon and its subregions, Sahel and Brazilian Nordeste droughts, Atlantic and other ocean basin tropical cyclone frequency and intensity, droughts and pluvial episodes in California and the American Midwest, and winter temperatures in North America and Eurasia.

In collaboration with NOAA, which has operational monitoring and prediction responsibilities as well as research and development needs, NASA/MTPE should help to develop the best possible monitoring and predictive assessment procedures and test them out in experimental mode. Potential test facilities for this purpose include the International Research Institute (IRI) Core Facility and Application Centers, which will have the responsibility to develop specific regional assessments based on global assessment inputs.

IV. Links to Other NASA-Supported Activities

Links to Pathfinder and other MTPE Data Activities: Several Pathfinder remotely sensed data sets (AVHRR, TOVS, GOES, SSM/I, SMMR, TOPEX, and NDVI) will provide critical input for seasonal-interannual research studies, especially for process studies and parameterization development. GSFC/DAO data assimilation products are currently made available to users through the EOS Data Information System and the GSFC DAAC. EOSDIS will have the responsibility for quasi-operational production of these data sets in 1998 and beyond. Although model-assimilated data sets are expected to be the primary data source for most studies, EOSDIS and its DAACs will also provide Level 1 and 2 data sets for some special research studies that need to work with data that has not been synthesized on a global scale.

Links to Earth System Modeling: The modeling element of the seasonal-interannual focused activity has much in common with modeling activities on other time scales. Interactions of modeling activities at NASA/GISS, NOAA/GFDL and NMC, NCAR, LDEO, UCLA, and COLA with those at GSFC have developed. For example, the recently updated GISS model cloud parameterization scheme is being tested in the GSFC coupled model system and in the atmospheric model (GEOS) currently used by the DAO for data assimilation, and a convective parameterization scheme being developed at UCLA will be similarly tested. These kinds of collaborative activities need to be increased where appropriate. Although the seasonal-interannual modeling activity is not directed at development of a full-blown Earth system model for all time scales and all Earth system components, its proven successes in a more limited arena can be incorporated in more comprehensive models. It should be noted, however, that climate system models designed for seasonal-interannual applications are generally not appropriate for longer time scales without modification, including addition of other processes (e.g., deep ocean thermohaline circulation) that are relatively unimportant (and difficult to initialize) on shorter time scales.

Links to Carbon System Modeling: An important goal of Earth system modeling is to develop carbon system models capable of providing predictions of future atmospheric carbon dioxide levels required for decadal-to-centennial climate studies as well as for IPCC assessments and for

studies within the Global Analysis, Interpretation, and Modeling (GAIM) Program of the IGBP. The dramatic changes in the global carbon cycle that have been documented on seasonal and interannual time scales provide strong constraints on large scale responses of the carbon cycle to forcing on decadal-to-centennial time scales. A primary way to improve understanding of oceanic and terrestrial processes that cause carbon source and sink distribution is through the information gained from monitoring seasonal and interannual variability. Developing such a monitoring capability is an essential step towards development of carbon system models. Satellite observations (e.g., SeaWIFS), process studies (e.g., SIMBIOS), and atmospheric and oceanic GCM models that include these seasonal and interannual processes will all play a crucial role in achieving this objective.

Links to other MTPE major science themes:

- **Land-cover/land-use:** Seasonal-interannual variability has short-term implications for land cover and land use issues, especially drought occurrences and their effect on vegetation. Realistic representation of surface fluxes related to biospheric quantities such as leaf canopy structure, obtained through evaluation of data from field campaigns such as BOREAS and LBA, will improve the ability of coupled seasonal-interannual models to simulate the interactive relationship between the land surface and the atmosphere. AVHRR and Landsat imagery provide a basis for quantifying seasonal-interannual changes in vegetation.

- **Atmospheric ozone:** Depletion of ozone by CFC's in the stratosphere, especially in the South Polar region, is modulated by the QBO, which is largely responsible for ozone interannual variability. This variability may affect the structure of phytoplankton communities and has links to higher trophic levels as well as biogeochemical cycles, with feedbacks on climate. The QBO also has links to interannual climate variability. Better understanding of the QBO and ability to predict its detailed evolution will be of value to both themes. Also, stratospheric sulfate aerosols cause ozone depletion by an as yet not well understood heterogeneous photochemical mechanism. These aerosols also play a role in modulating seasonal-interannual climate variations.

- **Long-term climate change:** Climate change on time scales of decades to centuries cannot be evaluated reliably nor well understood without knowing the magnitude, frequency spectrum, and spatial distribution of natural variability on seasonal-to-interannual time scales. Current values of these parameters must be determined from carefully analyzed observational records with sufficient uniformity and continuity, and future estimates must rely on model simulations. For example, significant changes in the decadal frequency of ENSO appear in the historical record, but their detailed explanation is currently lacking. Also, seasonal-interannual variations modulate oceanic carbon uptake and release, which may have consequences for decadal and longer climate trends. However, climate system models designed for seasonal-interannual applications are generally not appropriate for longer time scales without modification, including addition of other processes (e.g., deep ocean thermohaline circulation) that are relatively unimportant (and difficult to initialize) on shorter time scales.

- **Natural hazards:** An ability to accurately monitor and predict major climatic events such as severe winters, unusually hot summers, droughts, prolonged wet periods leading to flooding, and unusually active hurricane seasons are a primary goal of the seasonal-interannual focused activity. Other natural hazards such as fisheries depletion and coastal flooding are related to climate system fluctuations (e.g., El Niño) and may therefore be predictable. The seasonal-interannual focused activity especially needs to coordinate with the natural hazards activity on development of appropriate assessment strategies.

- **Links to EOS and other observing missions:** Besides the use of many of the remotely sensed observational data streams from the AM and PM platforms, the seasonal-interannual activity is dependent on the GSFC/DAO data assimilation products, whose production, archiving, and dissemination will be shared by EOSDIS and the GSFC Distributed Active Archive Center (G-DAAC). In addition, the seasonal-interannual activity has potential links with several of the EOS Interdisciplinary Science Investigations. These linkages need to be developed or strengthened so that efforts are complementary and common objectives are achieved.

  Also, the GSFC/DAO will provide a context for interpretive processing and evaluation of data from new observing systems. For example, the DAO will provide necessary auxiliary data for the physical initialization of TRMM observations and ambiguity resolution of scatterometer surface wind stress data (NSCAT).

- **Links to new technology development:** Aside from new technologies required for advanced satellite based observing systems (e.g., the New Millennium program), which will not be discussed here, the primary technological requirement of the seasonal-interannual focused activity will be the provision of adequate computational resources, especially for data assimilation, modeling development and application, and climate assessments. Supercomputer technology is currently undergoing somewhat of a revolution, with a move away from the vectorized systems that have prevailed for the last two decades and toward massively parallel processor systems that may or may not be distributed architectures. It is essential that MTPE capitalize on this new computational technology, which is expected to increase computational capacity and throughput by several orders of magnitude. To this end, exploratory research to test out new coding practices and to benchmark new parallel computer systems has been conducted under the auspices of NASA's High Performance Computing and Communications (HPCC) program. NASA-supported coupled climate modeling and data assimilation groups have participated in HPCC.

  A greatly increased computational capability will allow higher resolution and/or multiple ensemble predictive simulations with coupled models. Higher resolution is expected to lead to more useful regional-scale predictions, and ensemble sets of predictions from slightly varied initial conditions will permit a more accurate estimation of the certainty or uncertainty of the overall prediction. Increased computational capability will also further the development of comprehensive ocean-atmosphere-land data assimilation.

V. Links to Other Organizations

Links to other U.S. agencies:

The MTPE seasonal-interannual focused research activity constitutes NASA's contribution to one of the four major science themes of the USGCRP as well as to the interagency GOALS and GEWEX research programs. The other primary agencies involved in GOALS are NOAA and NSF. Some research activities related to GOALS objectives are currently supported by two or all three of these agencies in collaborative funding arrangements. This sort of collaboration will continue and probably expand as GOALS gets underway. Similarly, NASA collaborates with the other agencies to achieve the objectives of the international GEWEX program and its several sub-programs. For example, NASA collaborates with NOAA's Office of Global Programs on observational and other aspects of GCIP. Some GEWEX sub-programs (e.g., ISCCP) involve large investments by NASA, as the lead agency.

Coordination with other agency activities is provided by the U.S. Global Change Program Office, by the interagency Committee on Environment and Natural Resources

(CENR), and by the Climate Research Committee of the National Research Council of the National Academy of Sciences. In addition, much coordination is done on a bilateral or multilateral basis with other agencies using less formal channels.

LINKS TO INTERNATIONAL ACTIVITIES:

The MTPE seasonal-interannual activity contributes through GOALS to the CLIVAR international program. Both GOALS and the NASA/MTPE activity have links to several other WCRP and ICSU activities, including the Working Group on Numerical Experimentation (WGNE), the World Ocean Circulation Experiment (WOCE), the Arctic Climate System Study (ACSYS), the Global Climate Observing System (GCOS), the Global Ocean and Terrestrial Observing Systems (GOOS and GTOS), and major parts of the multi-faceted Global Energy and Water Experiment (GEWEX). The most important of these linkages from the seasonal-interannual point of view are those with CLIVAR/GOALS, GEWEX, and CLIVAR/NEG-1 and 2. There are also potential interfaces with the reconstituted WCRP/IGBP Working Group on Land Surface Experiments and with the Biological Aspects of the Hydrological Cycle (BAHC) program of IGBP.

MTPE expects to provide experimental seasonal-interannual predictions to the International Research Institute (IRI) for evaluation. The recently established IRI provides a means to coordinate international modeling and assessment activities and analyze mitigation/response strategies in key regions.

VI. Future Plans and Expected Accomplishments

NASA/MTPE future plans for the seasonal-to-interannual focused research activity build on a strong foundation of ongoing observational, process and diagnostic research, modeling, and data analysis activities.

OBSERVATIONS:

MTPE has launched satellite instruments such as ERBS and TOPEX-POSEIDON and will be launching other instruments (SeaWIFS, TRMM, NSCAT, TPFO, and the EOS-AM and -PM suites) that will greatly improve global observational coverage of several key climate system parameters. In most cases, these parameters are important for both seasonal-interannual research and longer term climate change issues. The network of *in situ* observations that complement the remotely sensed data and are necessary for their calibration must be maintained and expanded. Where necessary, NASA will support deployment of *in situ* observations and field campaigns for calibration/validation purposes and has organized teams associated with each planned launch to do this. Otherwise, NASA will largely depend on other agencies, especially NOAA, and their international counterparts for providing *in situ* measurements. NASA/MTPE will work with NOAA and other national and international organizations to develop a more comprehensive Integrated Global Observing Strategy (IGOS) and to maintain or expand critical *in situ* measurements such as those provided by the TOGA/TAO array. Satellite instruments that will provide important data products for USGCRP research goals are listed in Table 2-1.

In addition to basic acquisition of individual satellite sensor data, there is a need to merge like data from multiple sensors into single field global data sets (e.g., ISCCP and ERBE global data sets). NASA has had an important role in the provision of such merged data sets and will continue this role in the future for both existing and planned satellite data.

Finally, NASA will make a commitment to providing continuity of satellite observations to the extent possible.

Table 2-1 (right): EOS Mission Support to USGCRP Research Goals: Seasonal and Interannual Climate-Related Events.

EOS Mission Support to USGCRP Research Goals: Seasonal and Interannual Climate-Related Events

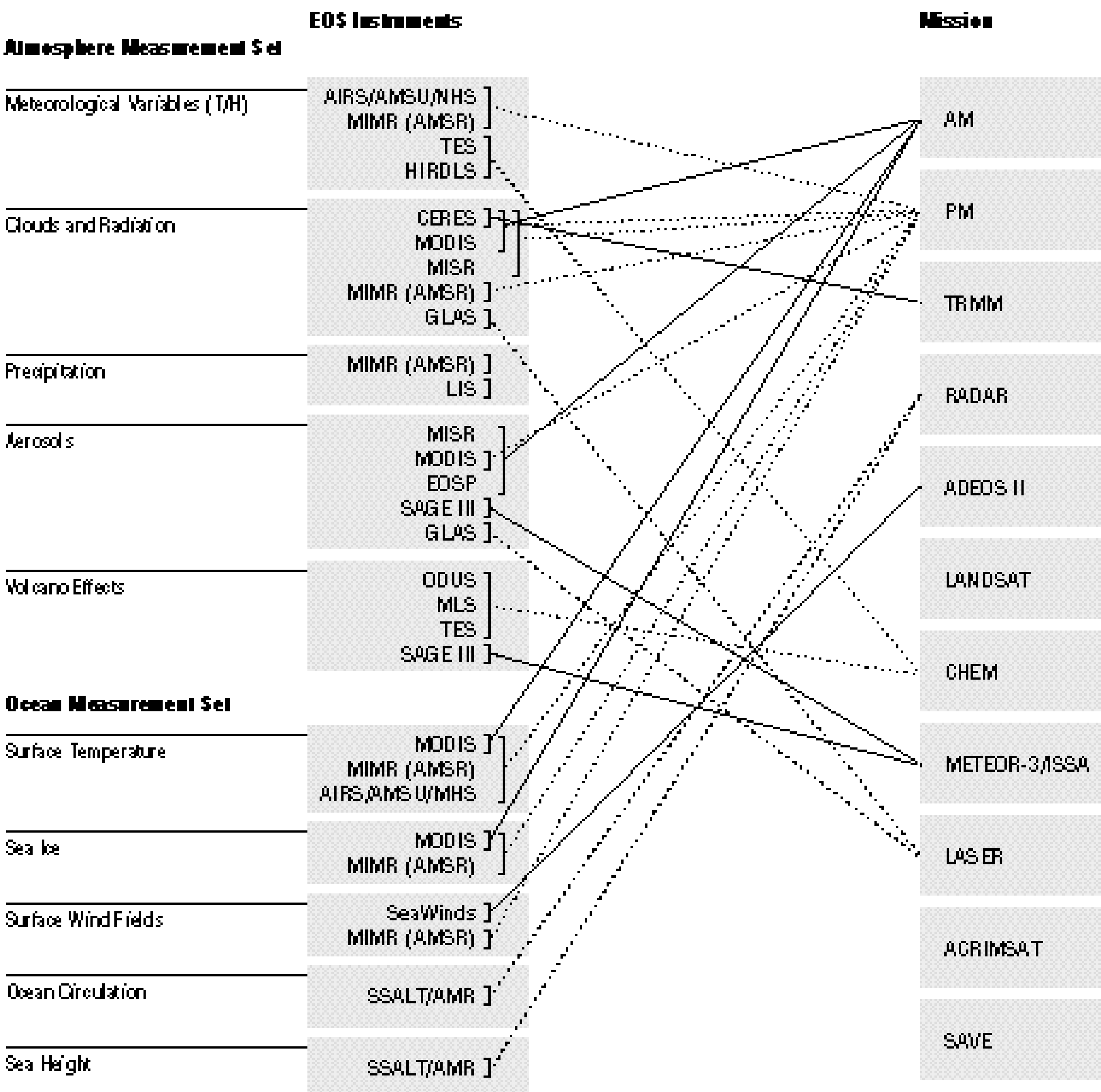


Table 2-1

NASA recognizes the need for such continuity if satellite data is to be useful for seasonal-interannual (and longer) variability purposes. NASA will work with NOAA on transitioning proven satellite technologies to operational systems. A comprehensive strategy for such transitions will be developed.

DATA ASSIMILATION:

GSFC/DAO has developed a prototype model-driven data assimilation system and has used it to produce a set of comprehensive and consistent analyses of global atmospheric data for studying seasonal-interannual variability on a global basis. The data assimilation system is undergoing improvements, including advanced analysis techniques to more accurately incorporate observational and model error in the system. By 1998, data collected after the analysis time will be included in the assimilation process by using a form of Kalman smoother. The assimilation system will be expanded to accept new types of observed data from NSCAT, TRMM, EOS-AM and -PM, CHEM, and other remote sensors including advanced versions on operational platforms. The system will also provide a data matrix for interpretation of some observing systems such as NSCAT and TRMM. Presently, land-surface, cloud-water, and cloud-ice parameterizations are being added to the assimilation system. Assimilation system versions designed for trace constituent transport and chemistry are also under development. The 1998 system will do state-of-science assimilation of moisture, rainfall, and hydrometeor observations as well as some land- and ocean-surface data. In response to GEWEX objectives, the DAO has targeted the representation of clouds and precipitation in the assimilation model for improvement. Overall, the DAO research activity will continue to progress toward development of a fully-coupled Earth system assimilation model that optimizes the use of satellite observational data. Initially, assimilation of combined surface and subsurface ocean data and of ecosystem data will be developed and tested as separate focused activities at GSFC or at other facilities before being combined with the DAO activity.

The DAO has and will continue to collaborate with related data assimilation activities such as that at NOAA/NCEP focused primarily on operational needs. This collaboration involves the exchange of data assimilation methodologies such as data quality control, objective analysis techniques, and choice of assimilating model. DAO will produce research quality data sets with broad scientific application retrospectively using all available data, with special emphasis on the optimal use of satellite and aircraft based remotely sensed observations. The NCEP activity is driven primarily, though not entirely, by operational needs and time constraints that may affect the completeness of the data base and the climatic consistency of the assimilation. There is, however, the possibility that much of the mechanics of the two data assimilation tasks can be integrated into one comprehensive system in the future through interagency collaboration.

Currently, there is no comprehensive source of integrated model-assimilated data sets for ocean observations, although data sets for specific observing systems have been produced experimentally. NASA/MTPE is working with other agencies to develop a focused program to address a well-recognized need for producing and distributing model-assimilated data sets which incorporate all available types of remotely-sensed and *in situ* ocean observations. As mentioned above, a longer-term goal is to combine atmospheric and oceanic data assimilation procedures in coupled model driven data assimilation.

Another need is the ability to assimilate data on much higher resolutions for limited regions and time periods (e.g., TOGA/COARE, GCIP, LBA), but in the context of the overall global climate system. One way to accomplish this is through use of nested assimilating models (with some attendant boundary problems); another way is by using a global model with variable grid, with highest resolution focused on the area of interest. NASA has initiated a pilot study of data assimilation using such a variable grid model.

Finally, data assimilation has the capability to become an important method for assessing the characteristics of physical parameterizations. By continuously confronting the assimilating model with observations, data assimilation provides a natural “testbed” for evaluating various schemes. For this to be feasible, it is important that the modeling community adopt the principle of modularity of model codes, in particular those for parameterization routines.

PROCESS AND DIAGNOSTIC STUDIES:

Many studies are currently underway, both at NASA centers and in the broader science community, that are improving our understanding of the key climate system processes that cause or modulate seasonal-interannual variations. The many TOGA-related studies, to which NASA has contributed along with NOAA and NSF, have greatly increased understanding of the dynamics of ENSO and have led to a limited predictive capability. Under the expanded scope of GOALS, these and other research studies will be carried forward. Some of the studies within the land surface component of GOALS (e.g., PACS) will be conducted in collaboration with GEWEX activities such as GCIP, ISLSCP, and GAME. NASA will especially support research efforts that address the process and diagnostic study needs listed in Section IIIb above, with emphasis on use of remotely sensed data. Many of these studies are dependent on successful completion of field campaigns, such as the recently completed TOGA/COARE, and their timing is a function of these campaigns.

Field experiments will be used to determine key climate processes and their representation in models for differing climatic regimes. Examples of relevant planned experiments are the GEWEX Asian Monsoon Experiments (GAME), which include sub-campaigns in tropical and subtropical humid lowland regions (Indo-China, Eastern China), a mountainous high plateau (Tibet), a taiga-tundra permafrost region (Siberia), and marginal seas (South China Sea). Other GEWEX field experiments that will lead to improved understanding and modeling of key processes are GCIP and LBA. These experiments are important for improving seasonal-interannual predictability of the coupled system, for helping to define possible Asian monsoon interaction with ENSO, and for evaluating the role of land surfaces and the hydrologic cycle in seasonal-interannual variability. NASA’s satellite and aircraft based observing capabilities will assist in maximizing the value of these projects and in relating detailed local and regional processes to global scale climate.

An important consideration of these studies is that in addition to improving our understanding of the processes involved in seasonal-interannual variability, they provide bases for improving the parametric representation of subgrid processes in global climate system models. MTPE management will need to help with improving the process whereby the results of pertinent process studies are converted into better parameterization schemes for models. The need for more efficient translation of process study results into useful model parameterizations was noted by a recent (1994) USGCRP meeting on climate modeling. A series of workshops that bring process researchers and related modelers together for this purpose will be held.

MODELING:

A key NASA/MTPE modeling activity in the seasonal-interannual domain is located at GSFC and is a joint effort between the Laboratories for Atmospheres and for Hydrospheric Processes. Thus far, this project has successfully coupled an upper ocean GCM to an atmospheric GCM and has coupled the atmospheric GCM to a parameterized land surface model. The coupled model system has been run without flux adjustments and has simulated ENSO-like behavior in the tropical Pacific (Fig. 2-4). It has also been used in a set of experiments that examined the relationships between SST anomalies and climate anomalies in continental regions as well as feedback between soil moisture and

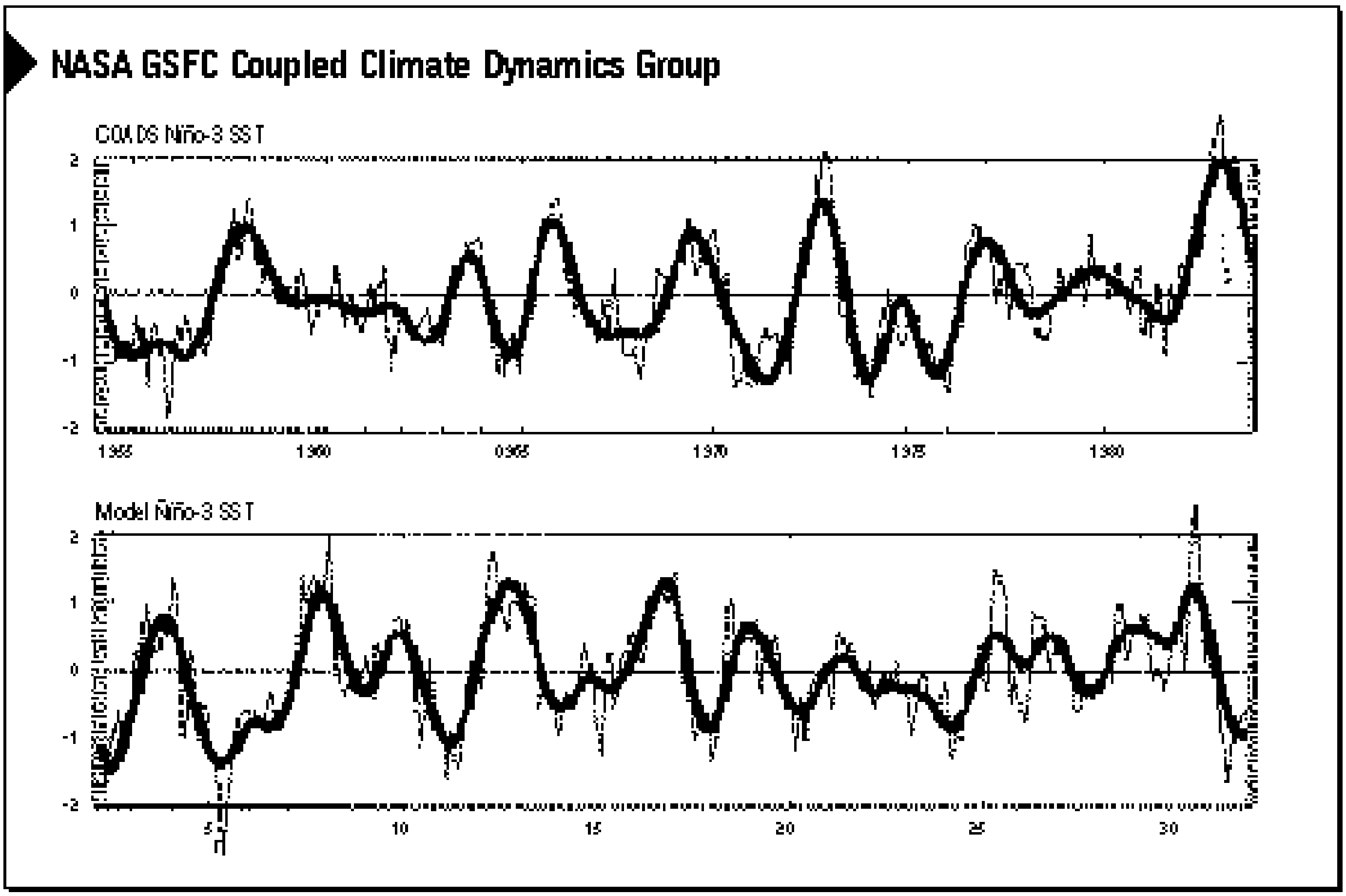


Fig2-1

Simulation of ENSO-like variations of sea surface temperature (SST) in the Niño-3 area of the tropical Eastern Pacific by the GSFC coupled model (lower panel), compared with observed SST variations from the COADS data set (upper panel). The year numbers for the model SSTs denote 32 years from the middle of an extended simulation. Vertical units are °C.

drought or pluvial conditions. Plans call for coupling a state-of-the-science sea ice model that has been developed independently to the ocean and atmospheric models. This coupled model system is well-positioned to develop into a strong modeling capability for experimental predictions of seasonal-interannual climate variations, both those associated with ENSO and those related to other causes, within the next few years. It is also a candidate to provide the modeling basis for coupled climate system data assimilation. A similar candidate activity has been developed at the Jet Propulsion Laboratory. These activities will permit NASA/MTPE to contribute significantly to the modeling and prediction objectives of both GOALS and GEWEX.

In addition to the above activities, MTPE currently provides support of several other relevant modeling activities within NASA centers, at universities, and at other research institutions. These other activities are engaged in developing improved parameterizations for clouds and water vapor in AGCMs, regionalizing global predictions, determining the limits of seasonal-interannual predictability related to ENSO occurrences and the Asian monsoon, modeling the atmospheric and land branches of the hydrologic cycle, modeling tropical air-sea interaction and its affect on Madden-Julian oscillations, and modeling the latitudinal and regional climatic effects of major volcanic eruptions. Support for efforts of these kinds will be continued and expanded in scope where feasible, and will be coordinated with MTPE coupled modeling activities. Again, it is important that computer codes for model components and parameterization schemes be modular in order for the results of these studies to be tested in more comprehensive system models.

MTPE coupled modeling activities will continue to evolve and will coordinate efforts with other modeling activities that are currently used for ENSO predictions as well as with activities that rely largely on empirical tools for seasonal-interannual predictions. There is a need for standardized intercomparison of ocean and coupled climate system models similar to the ongoing Atmospheric Model Intercomparison Program (AMIP) and the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS). MTPE will participate in setting up appropriate model intercomparison projects. As a start, GSFC and COLA scientists have initiated an ocean modeling intercomparison study.

Because seasonal-interannual vatriability (e.g., ENSO events) may have a pronounced effect on ocean ecosystems (e.g., phytoplankton and fisheries), an ocean ecosystem component needs to be coupled to the physical climate model. MTPE will develop plans to improve ocean ecosystem modeling and link it to modeling of the coupled system. Similarly, land surface model components need to improve their existing representations of ecological stress factors and include them in coupled system models.

ASSESSMENTS:

MTPE assessment activity on seasonal-interannual time scales is very limited thus far. The Hydrospheric Processes Division at GSFC has advanced the status of experimental ENSO predictions with partial support from NOAA. Plans for a more comprehensive role in seasonal-interannual assessments need to be developed in conjunction with the MTPE's Natural Hazards Program and with various elements in NOAA and ONR. Institutional arrangements need to be developed for the implementation of response actions based on predictive assessments. NOAA will have the mandate for operational assessments through its Center for Climate Prediction, but NASA/MTPE should make significant contributions to developing experimental assessment procedures that, if successful, can become operational. The potentially important value of satellite-based observations for seasonal-interannual assessment, and the conversion of these observations into useful information for assessments, should be the driving motivation for MTPE's seasonal-interannual assessment role.

VII. Summary

An ability to monitor and predict significant variations of the climate system on seasonal-to-interannual time scales is of great importance for many socioeconomic interests in the United States and in other countries. The economic payoff of useful predictions of events like El Niño and its various regional effects or of droughts in the U.S. agricultural heartland should be immense. All interests have a stake in reducing the hardship caused by these naturally occurring events through appropriate responses to accurate monitoring and reliable prediction.

However, the tasks of providing sufficiently accurate monitoring on a global basis and providing sufficiently reliable predictions of future significant events are still in an early stage. Much additional research and development will be needed before a level of global coverage, accuracy, and reliability is reached that will provide consistent socioeconomic benefit.

This plan describes the major research steps that need to be taken to achieve the goal of a viable capability to observe, understand, and predict seasonal-interannual climate system variations and to provide useful assessments to socioeconomic interests, and has indicated the role that NASA/MTPE should have in this process. The research effort proposed is consistent with the objectives of GOALS and GEWEX and will be an essential contribution to the international CLIVAR program. Since this is a research strategy document and not an implementation plan, the general directions of MTPE involvement in seasonal-interanual research are indicated but not specific, detailed plans. This document should provide a guiding framework for identifying specfic research topics and developing detailed plans for them.

The MTPE activity focused on seasonal-interannual climate variations builds on a strong existing basis of current and planned observing systems, data synthesis, process studies, and modeling development and application. These individual activities need to be brought into better coordination with one another and focused more explicitly on the problem of seasonal-interannual variability. MTPE needs to form a stronger partnership with other involved agencies, especially NOAA, to tackle this problem in the most efficient way possible, given the available resources. MTPE also needs to strengthen ties with national and international programs, such as GOALS and GEWEX, that have overlapping interests and can provide important contributions to the effort.

The fundamental basis for NASA/MTPE's involvement in seasonal-interannual research should be its satellite-based observational capability, both current and planned, for global coverage with continuity on time scales of 15 years or more that are necessary for developing full understanding of the dynamics of seasonal and interannual fluctuations, such as those of ENSO and the hydrologic cycle, and improving their predictability. Also important to this effort is MTPE's commitment to a sustained effort in coupled ocean-atmosphere-land modeling and in developing a coupled Earth system data assimilation capability.

NASA/MTPE, in concert with other U.S. agencies and the broader scientific community, is well positioned to have an important role in research on seasonal-to-interannual climate variations that will lead to major improvements in monitoring and prediction and consequent large social and economic benefits.

This section was drafted by Kenneth Bergman with major input by Antonio Busalacchi and helpgul contributions from many other NASA and non-NASA scientists. Timelines and expected milestones are in the process of being determined and will be appended to future versions of this plan. For more information on NASA's seasonal-to-interannual climate research activities, contact Dr. Kenneth H. Bergman at 202-358-0765 or at kenneth.berman@hq.nasa.gov

Section 3

Natural Hazards Research and Applications

EXECUTIVE SUMMARY

Thousands of human lives and billions of dollars are lost every year to natural disasters. While natural hazards are inevitable manifestations of Earth processes, they need not inevitably result in disasters.

NASA can assist society in reducing losses of life, casualties and property and reducing social and economic disruptions from future natural disasters. Through the development of technologies designed to observe and understand the Earth the Agency possesses a remarkable inventory of tools which can be effectively developed and applied to understanding natural hazards, characterizing natural disasters, and monitoring conditions that may lead to such events. This document describes a new Natural Hazards Research and Applications focus in the NASA Office of Mission to Planet Earth (MTPE) Science Division through which these approaches will be developed and brought to bear on reducing the disastrous consequences of hazardous events.

The program's initial earth science research priorities will be in selected aspects of disaster reduction where the technology pathway is understood and significant advances may be anticipated within the decade:

- What is the relationship between pre-, co-, and post-event regional surface deformation and seismic and volcanic activity?
- How can we use satellite-derived parameters such as topography, land cover, rainfall, soil moisture, snow cover (and water equivalent) and snow melt to improve the assessment of local and regional flooding risks?
- How is global seasonal-interannual climate variability reflected regionally through the occurrence of floods, monsoons, droughts, and the severity and frequency of storms?
- How does global sea level change find regional expression in severity of coastal hazards such as extreme storm surges, regional subsidence, flooding, erosion, and regional bathymetric changes?

Because natural disasters transgress political geographic borders and many disasters have far-ranging international consequences, international cooperation in understanding, characterizing and developing strategies to mitigate natural disasters is also essential. The role of MTPE will be to:

- Coordinate the unique contributions of NASA in remote sensing analysis, space technology development, and modeling.
- Sponsor and carry out research to understand those Earth processes that lead to natural hazards and use this understanding to develop methods for risk assessment.
- Develop and apply space technology which can be used to characterize hazards and reduce disasters, including:
  - collaboration with disaster managers; and
  - transfer of NASA-developed technology in readily usable form to the agencies with hazard predictions and disaster mitigation and response requirements.
- Coordinate with foreign agencies' space-based research and observation programs in natural disaster reduction.

Natural disasters are a recurring threat to humanity and our progress in this field should go beyond Research and Analysis toward routine implementation for a tangible, recurring benefit to society. Thus, in addition to addressing the scientific questions outlined above an initial goal will be the transfer of robust technology to the responsible agencies. This does not mean that NASA will declare victory and close shop with respect to a specific natural hazard or technological approach, but it is our intent to design programs that may phase out so that others may begin.

Thus deliverables products and scientific progress include: assessment of the usefulness of precise correlation between surface deformation and seismic or volcanic events and (if assessment proves the correlation is a valuable forecasting tool) transfer of the operational responsibility for these observations. Similarly if factoring in the remotely-sensed geophysical parameters proves improves flood, drought, or coastal hazard risk assessment or forecasting, the next step is developing a pathway to assure the incorporation of this information into operational programs.

In parallel with research and technology development and transfer activities we will continue the broader dialogue within and external to NASA. An international ad hoc working group on the use of the world's remote sensing capabilities for emergency response and relief has been formed under the Committee on Earth Observation Satellites and is chaired by NASA. The focus of this group ultimately reduces to issues of timely exchange of readily usable data. Although the issues are complex, ranging over policy (e.g., emergency access to data restricted for commercial or security reasons) to compatibility of format, avenues of information transfer, conventions for ready interpretation, etc., there is a growing sense of international motivation.

◆ ◆ ◆

I. Introduction

Natural hazards are inevitable manifestations of Earth processes but need not be inevitable disasters. NASA can assist society in reducing losses of life, casualties and property and reducing social and economic disruptions from future natural disasters. Our vision is to contribute to the scientific understanding of Earth processes and conditions that lead to natural disasters, apply NASA-developed, Earth-science inspired technology to mitigation of risk, transfer demonstrated technology to responsible federal and state agencies, and develop international conventions for timely exchange of space-based information relating to disastrous events.

Thousands of human lives and billions of dollars are lost every year to natural disasters. Through the development of technologies designed to observe earth science parameters NASA possesses a remarkable inventory of tools which can be effectively developed and applied to understanding natural hazards, characterizing natural disasters, and monitoring conditions that may lead to such events. This section describes a new Natural Hazards Research and Applications focus in the NASA Office of Mission to Planet Earth (MTPE) Science Division through which these approaches will be developed and brought to bear on reducing the disastrous consequences of hazardous events.

Because of the immediate humanitarian and economic effects of natural disasters it is critical that NASA act now to pursue practical applications in partnership with the responsible operational U.S. government agencies. Because natural disasters transgress political geographic borders and many disasters have far-ranging international consequences, international cooperation in understanding, characterizing and developing strategies to mitigate natural disasters is also essential. Several NASA Offices in addition to Mission to Planet Earth which currently support various aspects of natural disaster reduction can contribute to a coordinated agency-wide Natural Disaster Reduction Program: Space

Access and Technology, Management Systems and Facilities, Life Sciences, and Space Communications. The role of MTPE will be to:

- ◆ Coordinate the unique contributions of NASA in remote sensing analysis, space technology development, and modeling;
- ◆ Sponsor and carry out research to understand those Earth processes that lead to natural hazards and use this understanding develop methods for risk assessment;
- ◆ Apply and develop space technology which can be used in characterizing hazards and reducing disasters, including:
  - – collaboration with disaster managers;
  - – transfer NASA-developed technology in readily usable form to the agencies with disaster mitigation and response requirements; and
- ◆ Coordinate with foreign agencies' space-based research and observation programs in natural disaster reduction.

The program's initial earth science research emphases will be in selected aspects of disaster reduction where the technology pathway is understood and significant advances may be anticipated within the decade. These will include:

a. Characterization of the relationship between pre-, co-, and post-seismic regional surface deformation and seismic and volcanic activity through:
   1. Application of Global Positioning System dense array technology
   2. Acquisition and analysis of time series of synthetic aperture radar (SAR) images for SAR Interferometry (SARI).

b. Multi-faceted approach toward assessing local and regional flooding risks through retrospective studies, watershed modeling, incorporation of satellite-derived parameters such as topography, land cover, rainfall, soil moisture, snow cover (and water equivalent) and snow melt. Related to this (and requiring close interaction with the MTPE enterprise researching seasonal-interannual climate variability) is a longer-term research objective to develop understanding of the effects of year-to-year global or large scale climate variations on the occurrence of floods, monsoons, droughts, and the severity and frequency of storms.

In addition to these areas, the Natural Hazards Program will continue or pursue numerous other research projects on disaster-generating Earth processes, bringing new topics to forefront as other focus areas are resolved. Furthermore, MTPE will lead the development of a coordinated NASA-wide Program in natural disaster reduction. MTPE will explore the feasibility of dedicating NASA remote sensing technology to natural disaster reduction where it is not feasible to transfer the technology (and thus the responsibility) to an operational agency.

II. Background

Numerous agencies have requested the assistance of NASA's remote sensing capabilities, space-based geodetic data, and communications technologies during and immediately following natural disasters. Improvement in timeliness and precision of observation is at a point where disaster warning, risk assessment and time-varying risk analysis are now feasible.

The Natural Hazards Program at NASA has many roots in the MTPE Science Division. Among dozens of efforts, examples include:

- ◆ Development decades ago in meteorological satellite technology which has enabled the National Weather Service to track storms and hurricanes;
- ◆ Development of small receiving/processing work stations deployed in third world locations vulnerable to monsoon storm and flood;
- ◆ Prototype communications "pager" which can reliably and inexpensively provide disaster warnings to people in remote areas;

- ◆ Joint sponsorship of two U.S./Japan International Space Year Workshops (in 1987 and 1991) that focused on the requirements of high-temporal satellite observations of natural disasters;
- ◆ EOS Interdisciplinary Investigation committed to developing NASA's role in volcanic hazards research and applications;
- ◆ Agreement with NOAA and FAA to provide timely information on location of volcanic plumes for air traffic safety;
- ◆ Continuing dialogue between NASA's Earth Observations Commercial Applications Program and the Federal Emergency Management Agency (FEMA) to define remote sensing data requirements related to disaster characterization;
- ◆ Tactical use of airborne thermal sensors to locate and characterize urban and forested wildfires (at the request of the U.S. Forest Service, the California Office of Emergency Services, the Los Angeles County, the city of Scottsdale, Arizona);
- ◆ Airborne SAR views of flooded areas where optical remote sensing from aircraft or satellite is obscured by weather, for post-event assessments of damage;
- ◆ Refinement of space-based geodetic techniques and synthetic aperture radar interferometric technology that are both capable of measuring crustal motion to a resolution finer than one centimeter.

In addition, there is broad international and domestic interest in a preliminary proposal to integrate existing space-based activities to combat all aspects of natural disasters (the GEOWARN proposal). More realistically the recently established Committee on Earth Observation Satellite Task Group on Natural Disasters chaired by NASA is exploring means of applying existing or planned space-based systems to disaster response and relief measures.

What has lacked in these individual contributions is a coordinated sense of Agency purpose or charter in the area of natural disaster reduction. The Agency has demonstrated its ability to make isolated, but tangibly useful contributions. Consequently as national and international fora such as the Committee on Environment and Natural Resources (CENR) and the International Decade of Natural Hazard Reduction (IDNDR) enunciated national requirements and priorities, and as NASA has received a growing number of queries and requests, agency response and responsibility has developed along numerous paths. NASA has recognized that the next step toward meeting this growing involvement is to establish a new program focus in natural disaster reduction.

III. Program Elements

There are three aspects to the NASA MTPE Natural Hazards Program. A brief description of each follows:

A. Understand Earth processes which can lead to natural disasters.

B. Utilize existing or planned technology to aid in understanding hazardous processes, risk assessment, and disaster characterization.

C. Coordinate with international space-based agencies' research, observation, and flight project development programs in natural disaster reduction.

A. Understand Earth processes which can lead to natural disasters. The Initial Emphasis will be placed on:

- ◆ **Seismic Hazard:** Continue to improve our ability to understand local tectonics and to relate these to seismic hazard vulnerability through advanced space geodetic techniques such as the dense Global Positioning System (GPS) arrays and synthetic aperture radar (SAR) interferometry, the approaches highlighted as two of the three most promising emerging technologies at the 1994 White House Conference on Earthquake Loss Reduction.

◆ **Regional Consequences of Short Term Climate Variability:** Building on the progress in Seasonal-Interannual Climate prediction and forecasting of transient climate anomalies such as El Niño, a longer term research objective is to develop a quantitative understanding of disastrous regional manifestations of short-term climate fluctuations such as flooding, more frequent or severe storms, and drought. NASA is poised to improve the quality of local and regional flood forecasts and risk assessments, using watershed models incorporating satellite-derived parameters such as topography, land cover, recent rainfall history, soil moisture, snow cover (or its water equivalent) and snow melt. Similarly forecasting of other extreme events may be regionally sharpened by satellite land cover time series and snow accumulation and snow melt forecasting in regional drainages.

Additional Activities

◆ **Global Sea Level Change:** Characterize global sea level change and possible mechanisms through a combination of satellite altimetry, regional tide gauge/geodetic networks, time varying gravity, global sea surface temperature time series observations. While a change in sea level doesn't fit within the traditional concept of a natural disaster as a short duration crisis, it is likely that such rise would be manifested in the increased occurrence of coastal flooding and erosion. The consequences to coastal habitability and long term infrastructure planning are profound, thus the topic is included in this prospectus.

◆ **Wildfires:** The emphasis in the near future will be on characterization (location and intensity) and modeling of wildfire development based on the understanding of local weather conditions and topography. Regional monitoring of NDVI, soil moisture, meteorology to develop short term vulnerability assessment is also anticipated, as well as tactical communication to emergency personnel in the field.

◆ **Volcanic Hazards on the Ground and in the Air:** New capabilities to monitor precursor activity at a volcano have emerged in the development of airborne and satellite capabilities to detect as centimeter-scale deformation of a volcano through INSAR and GPS techniques, changes in thermal anomalies, and the ratio of different volcanic gases. Digital elevation models can also be used to predict the most likely paths of lava flows, lahars and pyroclastic flows, thereby enabling advance training on hazard mitigation to be directed towards populations at greatest risk. Once an eruption is in progress, new algorithms to detect and monitor eruption plumes in near real-time provide a degree of warning in remote locations that has hitherto been unavailable

◆ **Landslides:** Develop techniques for assessing slope vulnerability through mapping surface cover, topography, soil moisture, and other soil properties.

◆ **Coastal Hazards:** The near-shore coastal environment offers a unique setting where geologic, ecologic, oceanographic and meteorological factors can lead to extreme storm surges, regional subsidence, flooding, regional bathymetric changes due to sediment redistribution/resuspension, pollution concentration/dispersion. Relates closely to Sea Level Change activities.

B. Utilize existing or planned technology to aid in understanding hazardous processes, risk assessment, and disaster characterization.

Natural hazards may be viewed as accelerated manifestations of global change on a local to regional scale, and thus many Earth Observation emphases developed in NASA are well suited to natural hazards applications. Examples include the techniques developed for Tropical Rain Mapping Mission to measure precipitation (especially when tied to other satellite meteorological observations); sea state scatterometry for more accurate determination of

storm strength and sea-state; sea surface temperature measurements, satellite regional NDVI time series, and Total Ozone Mapping Spectrometer for unambiguous identification of major volcanic eruptions. These space-based technologies will be thoroughly integrated with ground-based observations where appropriate.

Considerable work is needed to interpret these new satellite-based techniques confidently. An example is the use of SAR interferometry to detect topographic change due to earthquakes and volcanic activity. SAR data are affected by local meteorology and the ionosphere, as well as surface processes that can decorrelate the images. Such effects may be correctable through the use of dense GPS arrays on the ground which not only provide measurements of the three-axis movement of the ground, but can also be used to determine the local total column water vapor content of the atmosphere, which is one of the largest sources of error in the radar data.

In another effort to validate digital elevation products based on SAR interferometry, the Topography and Surface Change Program will provide crucial insight into how accurately airborne and orbital interferometry work over diverse terrains. Such knowledge will be crucial for hydrologic, landslide and volcanologic risk assessment.

A study group has been established to examine the concept of a network of low-cost, student-run satellite ground receiver stations which would serve primarily as a research and education tool but would also be capable of providing useful real-time information to responsible officials in case of a disastrous event. The conversion or “recruitment” of existing facilities (such as high data rate X-band receivers currently used for other research purposes) to this end will be included in the study.

An important aspect of technology utilization is the transfer of its usefulness to operational disaster practitioners. There are two critical components in this regard: one is the provision of pertinent information on demand to different agencies in near real-time, and the second is the transfer of NASA-developed technology, where appropriate, to the end user agency. Thus technologies and capabilities must be developed in conjunction, coordination, and collaboration with the organizations envisioned as ultimately responsible for their application. Acquisition of satellite data via direct broadcast from the satellite, analysis of the data via automated algorithms to detect anomalies, and the development of lines of communication and responsibility between NASA and responsible agencies is one route for cooperation, while complete transfer of capability may be preferable in other situations. At the top of the national level is the Federal Emergency Management Agency (FEMA) through which linkages are established with regional and state offices. Coordination among other federal agencies will be achieved individually (for example with NOAA, USGS, FAA, and Coast Guard) and collectively through the Subcommittee on Natural Disaster Reduction (SNDR) of the CENR. At the international level coordination will be achieved with the USAID’s Office of Foreign Disaster Assistance (OFDA) and international agencies such as the World Meteorology Organization (WMO), the Food and Agricultural Organization (FAO), UN Department of Humanitarian Affairs and the International Decade for Natural Disaster Reduction. An important component of this element is the coordination of NASA’s many activities in this arena across many NASA Offices.

C. Coordinate with International Space Agencies’ Research, Observation, and Flight Project Development Programs in Natural Disaster Reduction.

Recently NASA has been asked to lead a Task Group to study the use of the international Committee on Earth Observation Satellites’ facilities for natural disaster applications. The intent is to develop an international convention for the timely use of existing or planned space-based observations during disastrous events to assist in response and relief efforts. Several of the world's space agencies (notably Japan, Europe, and India) have already begun initiatives focused on the application of space technology to disaster reduction. There is now a rich selection of satellite and remote sensing technology under consideration and development.

IV. Links to Other Programs

A. Planned and Future Campaigns and Flight Projects

Many projects and programs already planned or in existence contribute to the goals of the MTPE Natural Hazards Program, some by specific design and others because the phenomena and processes of interest play an important role in other fields in NASA MTPE. Following is a partial list of current activities and near term plans.

Earth Science Research and Applications in Natural Hazards

◆ **Dense Array Technology**: So little is known about the relationship between crustal surface change and seismic events that a multi-year data base tracking surface movement in a seismically active area would open a new area of promise toward earthquake forecasting—or close this avenue. This is the motivation for the development of the concept of a dense array of high resolution, permanently installed, continuously operating GPS receivers. When fully operational this system will be complemented with contiguous remote sensing SARI information. Among the last three large earthquakes in California, two occurred along previously unmapped faults (Landers 08/92, Northridge 01/94). At a minimum the array of receivers will identify anomalous motion along buried thrust faults (along which the Northridge Earthquake occurred). Positive temporal correlation between pre-seismic displacements and seismic events would open a quantitative new approach to the complex, unyielding problem of identifying earthquake precursors. Deployment of a Pilot Array began in 1990, was expanded following the Northridge Earthquake, and will be incorporated as the Southern California Integrated GPS Network (SCIGN) across the Los Angeles Basin beginning in 1995. A five- to seven- year observation period will be concluded by the gradual withdrawal of NASA support and concomitant increase in operations support by the U.S. Geological Survey. NSF is also involved in funding the operation of the project through its support of the Southern California Earthquake Center.

◆ **Characterization of Sea Level Change:** In addition to characterizing global sea level change it is important to identify its causes. NASA maintains leadership in four avenues of sea level change research: actual measurement through ocean altimetry (TOPEX/Poseidon, ESA's ERS-1, -2); estimation inferred from changes in ice cap volume (expected from GLAS and, to a lesser degree, *from* Canada's Radarsat); discrimination between regional and global sea level change through tying regional fiducial geodesy to regional tide gauges (International Geodetic Network with European, Asian, Oceanian, and NOAA participation); and discrimination between sea level rise due to thermal expansion of oceans vs. additional mass of water (time-varying gravity field from series of orbiting GPS receivers, World Ocean Circulation Experiment deep ocean hydrographic temperature time series). An organizational meeting held November 1995 at the University of Miami to coordinate with international and domestic colleagues was also supported by NSF and NOAA. A major recommendation from this meeting calls for coordinated observations from 1996–2000.

◆ **Topography and Surface Change:** The Science Team selected in 1995 consists of 36 three-year investigations from traditional fields of hydrology, ecology, glaciology, geology, geodynamics, natural hazards, modeling and observing technique development. These studies will acquire and analyze digital topographic data in the pursuit of scientific understanding of static and dynamic topography, Earth surface processes, and interactions among Earth systems. In addition, the Working Group will provide a forum for information transfer and will make/refine recommendations on data requirements for future airborne/spaceborne observations of topography and its changes. NASA is continuing the development of unique capabilities to measure the Earth's surface topography at high resolution and accuracy and detect minute changes in this surface including Synthetic Aperture Radar (SAR) interferometry, laser altimetry, and GPS, that will be utilized by this program.

- **Floods workshop:** A NASA-organized workshop was held in August 1995 to evaluate the means to improve local and regional flood forecasting, by incorporating satellite-derived parameters such as topography, land cover, rainfall, soil moisture, snow cover (or water equivalent) and snow melt in watershed modeling and developing the applications of these models to assessing the vulnerability to flooding. Interagency attendees included USGS, TVA, DOD, NOAA. Recommendations from this workshop will be incorporated in the call for natural hazards-related proposals issued during July 1996.

- **Deployment of NASA DC-8 to the southeast Pacific**: The project is scheduled in the October/ November 1996 timeframe and is motivated in part by requests for cooperative flights over coastal topography of Indonesia, Malaysia, Philippines and Japan, and in part by common Earth science research interests with Australia. The minimum anticipated result is improved assessments of storm surge risks, but watershed modeling, seismic and volcanic risk assessment, land use dynamics, etc. are also planned in several regions.

- **International Geodetic Network (IGN)**: NASA leads the development of GPS technology and coordinates space-based geodetic observations in some 45 countries worldwide to monitor global rates of plate motion and crustal deformation. Besides identifying regions of anomalous surface deformation which may be related to seismic events, these stations provide fiducial geodetic location control for remote sensing and for tide gauges. Certain key GPS receivers in the network also provide precision tracking service for spacecraft carrying onboard GPS receivers, themselves a key to improved ocean altimetry and sea level characterization. The IGN also provides improvement to the definition of a stable, terrestrial reference frame centered at the Earth's center, a requirement for precise documentation of sea level change.

- **Dynamics of the Solid Earth (DOSE):** Beyond characterization of global tectonics accomplished by the IGN, the DOSE program focuses on regional to local areas of rapid crustal deformation in regions of active tectonic activity and on the processes driving solid Earth's dynamics, including atmosphere's angular momentum, ocean tides and currents, variation in the core flow dynamics and angular momentum transfer between the various components of this complex system. The time scales of interest range from millions of years for shifts in lithospheric plate configurations to seconds for a seismic event. This partial release of stress may result in another unstable juxtaposition as a result of sudden crustal motion. The current DOSE science working group completes its final year in 1996. The next phase will have a greater focus on seismic and volcanic hazard.

- **Electromagnetic precursor signals to seismic events:** These have been described in Asia and Russia for several years, but have only recently been discussed in the peer-reviewed scientific literature. NASA's interest in studying Earth's magnetic field is based on a desire to understand the core dynamics processes that lead to the generation of the Earth's magnetic field and to reversal of field polarity. The magnetic surveys that will be launched in the near future (Ørsted (Denmark, NASA, CNES) in March 1997, SUNSAT (South Africa, NASA, same launch as Ørsted), SAC-C (Argentina, NASA, Denmark) in late 1998, CHAMP (Germany, NASA) in late 1999 are expected to yield data that should allow testing of the proposed theories.

◆ **Interagency Coastal Hazards workshop:** Hosted in February 1996 by Louisiana State University, topics included approaches to improve our ability to forecast storm intensity and path through the use of improved models and satellite observations of sea surface temperature, sea surface state and wind velocities, humidity, cloud tracking, and direct measurement of wind velocities; and to improve our ability to forecast and warn of the effects of storm surges including consequences to beaches, local ecology, built environment, and pollution through the observables listed under flooding and severe storms.

Disaster Response and Characterization

◆ **Institutional Aircraft support of government requests for emergency aerial surveys:** The NASA airborne science remote sensing assets at ARC and SSC are available for emergency response through the provisions of the Federal Response Plan, and are activated by FEMA through official channels. Although contingent on availability of aircraft and sensors, response times have typically been within 24 hours. The assimilation of imagery products into the FEMA response process has yet to be perfected, however, and further cooperative development will be required in this area.

◆ **Wildfire Mapping:** Perhaps the most successful disaster-related application of NASA airborne assets has been in wildfire mapping. In response to requests from the U.S. Forest and Park Services, and various county and municipal fire departments, Thermal IR radiometry from ER-2 and C-130 aircraft has been used to see through smoke and provides real time fire mapping information to fire fighting teams in a timely and effective manner. Valuable lessons have been learned regarding data dissemination and interpretation, in what has proven to be an ideal application of NASA technology. New developments in information exploitation and distribution, such as satellite uplinks and portable Earth stations, could enable NASA to make a significant future contribution in this field.

◆ **Aircraft volcanic dust clouds warnings:** NASA cooperates with FAA and NOAA to provide satellite data on volcanic plumes for aircraft rerouting. Currently NOAA has an operational relationship with the FAA to provide warnings of potential or real volcanic ash hazards. However, current techniques for ash detection and mapping using AVHRR may be subject to improvement. In addition FAA is interested in detecting volcanic SO_2 clouds, which may be done using EP/TOMS, ADEOS/TOMS or some other space instrument making observations in the UV, visible, or infrared. This would include the development of real-time processing of sulfur dioxide measurements from the TOMS satellite, and the analysis of AVHRR data for plume detection and analysis of thermal anomalies. Inter-agency coordination is needed for data evaluation and assessment of the risk to the general population.

Online information

Under the aegis of the U.S.-Japan Science and Technology Agreement NASA has placed online (accessible to WorldWideWeb and Gopher interfaces) a database consisting of over 500 references (including abstracts) to papers on the application of space technology to disaster reduction (http://ltpwww.gsfc.nasa.gov/ndrd-cgi/ndrd). This compilation (complete through the end of 1995) is accessible via Internet and will be updated periodically in the future, The

Web site is also planned to become a "how-to" source for operational disaster management practitioners. In addition the Jet Propulsion Laboratory has a Hazards site on the World Wide Web (http:southport.jpl.nasa.gov) and Dartmouth College is supported by NASA to post real time flood disaster information (http://www.dartmouth.edu/artsci/geog/floods/Index.html)

B. Links to the other Four Integrating Science Themes

The Natural Hazards Program is linked to the broad goals of Global Habitability which was introduced in 1982 and led to the Global Change Research Program. It is thus intimately connected with GCRP insofar as changes in various aspects of the global environment are the major natural factors which result in disasters.

a. **land-cover and land-use:** The linkages range from fundamental issues of changing human settlement patterns in areas at risk from natural hazard to mutual interest in acquiring topographic data and land cover information to assess risk of flooding, landslides, erosion, drought.

b. **seasonal-interannual variability:** Linkage with this theme centers on characterizing the relationship between transient climate variations and consequent weather patterns, particularly over North America. The Natural Hazards Program will concentrate on the complementary tactical assessment of the consequences of this coupling (flooding, drought, erosion and sea level surges).

c. **long term climate change:** While the perceived increase in the frequency and severity of storms may be due in part to improved telecommunications (many phenomena would have escaped media coverage only a decade or two ago), there can be no doubt that the increase in population has placed a growing number of people at risk either from hurricanes, severe storms and storm surges, floods and droughts, or from earthquakes by virtue of the regional geography. On the other hand, part of the increase may actually be attributable to global climate change. MTPE's Earth system modeling effort will seek to shed light on this question and objectively document the possible relationship between severe weather events and large-scale climate anomalies.

d. **ozone:** Mutual interest in health and well being of TOMS for characterization of atmospheric sulfur dioxide.

C. Links to Pathfinder, other MTPE Data-Development Efforts, and Earth System Modeling

NASA has been and continues to be concerned with retention and continued use of the data it collects. The Natural Hazards Program will make use of such archives for baseline and retrospective studies.

An extensive archive of disaster-related remote sensing imagery has been accumulated by the NASA airborne science programs at ARC and SSC. This consists of high resolution digital and photographic data, collected in response to actual incidents, including hurricanes, floods, earthquakes, and major fires. The archive spans over approximately 20 years, and covers most of the major natural disasters that have occurred in this country during that time, including the Mt. St. Helens eruption.

The AVHRR and Landsat pathfinder data sets are also proving to be excellent sources of information for assessing the size, frequency, and duration of wild fires. Analyzing the size and peak temperature of the fire enables prediction of the effects of fire storms. Retrospective studies of the regional vegetation cover and topography can be used to identify areas of potential fire hazard. In terms of global change studies, fire size and temperature are also important because they control the gas species and their total mass that are released into the atmosphere. A lot of work is currently underway as part of the SCAR-C Project to evaluate the use of thermal infrared sensors for the mapping of forest fires.

D. Links to EOS Interdisciplinary Investigations

The Natural Hazards Program will tie into several of the investigations being carried out in support of the EOS missions. One EOS Interdisciplinary team is focused on the analysis of volcanoes, volcanic hazards, and volcanic input to the atmosphere. By mapping active and dormant volcanoes using EOS and other satellite-based sensors such as interferometric SAR, a baseline data set will be established against which to measure change. Change detection can take the form of monitoring the amount and relative abundance of different volcanic gases, changes in the release of thermal energy from volcanic craters, surface deformation due to shallow magma intrusions or subsidence of summit areas, or the identification of recently emplaced volcanic flows. Techniques are also under development to rapidly identify new volcanic eruption plumes, measure their temperature, altitude and topography in order to assess their potential impact on air traffic, and to quantify the rate at which gases and aerosols are injected into the atmosphere.

The real-time response that is required to use EOS satellite data for volcanic hazard mitigation is driving not only the development of new algorithms, but also reducing the access time to the data, and communication of the derived information to other communities. One of the recent developments has been the rapid reduction in the cost of direct down-link of EOS sensor data such as OCTS and MODIS and orbital imaging radars which places both ground station and data processing facilities well within the financial reach of typical university groups. For example, the interferometric processing of SAR data to detect surface deformation can now be done on a mid-range work station in a few hours.

The Amazon interdisciplinary investigation will make a strong contribution to the second initial focus of the Hazards research program as it combines topography, land cover, seasonal precipitation and snow melt forecasts to model regional flood risk. If the approach proves useful there, NASA will explore its utility in other ecosystems.

E. Infusing New Technologies

Several of the applications described above have been possible only because of the introduction of new technologies:

SAR Interferometry
Recent MTPE-sponsored research in synthetic aperture radar (SAR) techniques involved comparing the phase difference (interferences) between two scenes acquired over the same area; the technique is called SAR Interferometry (SARI). If the two scenes are acquired at the same time, they can be processed to produce a high resolution digital topography data set. If acquired at different times, they can be mapped against an existing topography map to determine changes of the order of centimeters or less.

Proposed Shuttle Radar Topography Mission (SRTM)
A third flight of the Space Radar Laboratory will modify the SIR-C/X-SAR hardware to pursue a flight project dedicated to providing a digital topographic data set over all of Earth's land surface between 60° north and south (13–16 m vertical resolution, 30m horizontal). NASA and the Department of Defense signed a Memorandum of Understanding to support this mission in July 1996. If acquired, the topographic database will provide important information in assessing risk of floods and landslides as well as providing important baseline against which topographic change can be compared in subsequent SAR interferometric observations. SRTM is manifested to fly in May 2000 and data processing is scheduled to be completed within 12 months of the flight.

A component of the SAR technology research and development is the combination of radar and differential GPS. The radar provides areal coverage, while GPS provides not

only time-continuous 3-axis motion data but also a means to correct for spurious phase shifts due to variations in atmospheric water vapor content.

LightSAR

The LightSAR project is being considered as a technology demonstration mission. The most recent advances in composite materials and hybrid structures (low mass, compact foldable antenna) and microelectronics (low power) would be applied to design a lightweight and low-cost SAR free-flying spacecraft. New deployable antenna concepts are also being investigated to further reduce mass and size (pre-launch), and hence reduce mission costs.

The current LightSAR concept is an L-band single-polarization (HH or VV) SAR with ScanSAR capabilities, launched to a 600 km altitude to enable 8-day repeat pass acquisition of SAR derived surface change detection. The instrument will have variable resolution modes with 5 m, 30 m, and 100 m options with corresponding swath widths of 25 km , 80 km and 250 km. Low-cost X-band distributed ground terminal stations will also be validated as part of this mission, as will a commercial operation scenario.

Global Positioning System technology

The instrument of choice for array technology is a receiver developed by NASA-JPL in cooperation with Allen Osborne Associates: the TurboRogue. In addition to yielding precise continuous location of ground site for seismic risk assessment GPS data are yielding data on precipitable atmospheric moisture comparable to water vapor radiometer measurements and may hold a key to enhancing ground-based severe storm forecasting and tracking.

The GPS-MET mission, launched in March 1995, carried a “ruggedized” TurboRogue receiver supplied by NASA. The mission was a highly successful demonstration of feasibility of low-cost, high performance onboard GPS technology. The atmospheric occultation of the GPS satellite constellation signals received by the GPS-MET receiver provided unique, high vertical resolution, information on atmospheric temperature structure and water content. This is the basis for the proposal to fly a constellation of micro-satellites carrying these GPS receivers, under consideration as a **New Millennium** project.

Shuttle Laser Altimetry

Laser altimetry from space was very successful demonstrated on the Space Shuttle STS-72 in January 1996, with a second flight scheduled for 1997. Quick analysis of data indicates geodetic quality altitude measurements with 1–2 m vertical accuracy in 100 m footprints, with anticipated post-processing precision of .5 m to 1.0 m. SLA could provide a high resolution, absolute elevation profile to complement the Shuttle Radar Topography Mission’s high resolution global topography (between 60° North and South latitude) data set, and current intent is to fly simultaneously.

It is further expected that the **Geoscience Laser Altimetry System** will be implemented as part of the **Earth Observing System** program to acquire high resolution topographic profiles over an extended period of time.

Hyperspectral Imaging spectrometers can be used to characterize drought- and desertification-related soil mineralization, and soil erosion and exposure of underlying bedrock. The high spectral and spatial resolution free flyers Lewis and Clark will provide a first opportunity to develop these applications from space.

Landsat-7 (Enhanced Thematic Mapper)

The Enhanced Thematic Mapper can also be used to detect alterations of the land surface and, additionally, thermal anomalies in wildfires and volcanic lava flows. Landsat observations provide large-scale mapping of volcanic and seismic zones, soil and vegetation properties and distribution, watersheds, vegetation and land surface changes.

Imaging Spectrometry

Ultra-violet and infra-red imaging spectrometers have enabled quantification of the rate of release of sulfur dioxide from volcanic craters. Thermal Infrared and mid-IR spectrometer techniques are emerging for use in measuring HCl, CO, OCS, and HF, the ratios of which change as eruption grows imminent. Low-cost airborne receivers under development at EOCAP (SSC) and the University of Hawaii. TOMS and the Earth Observing System's ASTER and MODIS are critical components of the volcanic hazards program plan. The combination of visible, infrared and thermal sensing of ground features and volcanic plumes and SO_2 characterization tracking will allow identification of eruption precursors, actual events, and ground and airborne consequences of eruption,

Real-time downlinks of aircraft observations. The Ames ER-2s have used direct, real-time downlinks of Thematic Mapper IR data in several operational cases for forest fire mapping in the Western U.S. This involves a line-of-sight transmission either to Ames or to a portable field unit. The latter proved quite valuable during the Yellowstone National Park firestorms of 1988. The STARLink system currently being installed on one ER-2 under funding from the Office of Space Communications will provide a world-wide, real-time uplink capability for high data rate imagery via the TDRSS system. Operational in 1995, it will be initially tested over wildfires in California.

F. Current Areas of Cooperation with Other U.S. Agencies

NASA has a wide and diverse collection of interagency cooperation and coordination between several NASA Offices and Centers and other government organizations and consortia. Coordination within NASA of these activities should be enhanced.

The chief instrument for coordination of federal agencies' activities in natural disaster reduction is the Sub-Committee for Natural Disaster reduction of the Committee on Environment and Natural Resources. NASA MTPE has been a member of this Sub-Committee since its inception and continues to coordinate its plans and activities with a wide range of federal agencies.

Responsibilities for efforts in natural disaster reduction at the national level focus on the Federal Emergency Management Agency. The Natural Hazards Program recognizes the importance of maintaining a close linkage with this agency and for that reason an MTPE liaison is co-located with FEMA. With the active support and cooperation of FEMA management the function of this Liaison Officer is to communicate FEMA's information and data requirements to NASA and advise MTPE on technology and research developments which NASA can undertake to satisfy them. Current discussions with NOAA aim in providing this liaison function to that administration as well.

NASA contributes to emergency response and disaster mitigation through a cooperative agreement with the Federal Emergency Management Agency under the Federal Emergency Response Plan (FRP). The Airborne Infrared Disaster Assessment Systems (AIRDAS) was developed and implemented at the Ames Research Center to support FEMA and the U.S. Forest Service emergency response efforts fire hazards. NASA maintains a fleet of aircraft equipped with an array of remote sensors which have been used to provide information vital to relief efforts for floods and hurricanes, in addition to supporting fire fighting efforts. Stennis Space Center maintains a Lear Jet equipped with remote sensors that is also used to support FEMA under the FRP. Although contingent on availability of aircraft and sensors, response times have typically been within 24 hours. The assimilation of imagery products into the FEMA response process has yet to be perfected, however, and further cooperative development will be required in this area.

Perhaps the most successful disaster-related application of NASA airborne assets has been for wildfire mapping. In response to requests from the U.S. Forest and Park Services, the U.S. Forest Service National Interagency Fire Center and California Department of Forestry and Fire Protection. and various state fire departments, IR data has been provided by Learjet, ER-2 and C-130 aircraft to fire fighting teams in a timely and effective manner. Valuable lessons have been learned regarding data dissemination and interpretation, in what has proven to be an ideal application of NASA technology. New developments in information exploitation and distribution, such as satellite uplinks and portable Earth stations, should enable NASA to make a significant future contribution in this field.

In addition to linking with research programs sponsored by other U.S. Agencies, NASA will monitor or potentially collaborate with major efforts aimed at filling information needs of the disaster community. Three notable projects of this type include the Global Emergency Management System (GEMS) program sponsored by FEMA, the ReliefNet program under the auspices of the Department of State, and the Disaster Relief Planning Program directed by the Department of Defense. The first two programs are Internet-based information dissemination systems currently under development. Remotely sensed data and information derived therefrom could be provided by NASA to enhance the capabilities of these systems.

GEMS is operating and universally accessible on the Internet. It provides extensive resources for disaster management ranging from current situation reports to images of the event. ReliefNet is under development and, while the lead has been taken by the Department of State, the project is international in scope involving over 200 participants thus far, and growing. ReliefNet is by far the most comprehensive and ambitious program of this type under development and its progress should be monitored. The Disaster Planning Relief Program is managed by the U.S. Army Space and Strategic Defense Command. Although primarily focused on enhancing the capabilities of military base commanders to respond to local emergencies, this program has demonstrated in the field the utility of real-time, space-based remotely sensed data for disaster relief through coordinated efforts with FEMA during the Midwestern Floods of 1993 and the flooding in south Georgia in 1994.

A broad variety of cooperative efforts within the Agency are directly aimed at tactical disaster mitigation and response. In addition to activities already mentioned at the Ames Research Center and Stennis Space Center in direct support of the Federal Emergency Response Plan, notable examples include:

- ◆ At the Goddard Space Flight Center, the Earth Alert Program, the Search and Rescue Mission Program, and three projects to provide information for emergency response on the Internet, under the Cooperative Agreement for “Public Use of Earth and Space Science Data Over the Internet,” sponsored by the High Performance Computing and Communications Program in the Office of Aeronautics. The three programs are the Bay Area Digital GeoResource (BADGER) project led by Lockheed-Martin, the Emergency and Crisis Management project led by the University of North Texas, and the Flood Management Enhancement Using Remotely Sensed Data project let by Sentar, Inc.

- ◆ The Jet Propulsion Laboratory is involved in the application of SAR to hazards research and monitoring through numerous projects and development of GPS receiver and array technology and is a member of the southern California Natural Hazards Consortium, which seeks to utilize emerging technology for disaster response and relief. JPL also manages the IGN.

- ◆ The Langley Research Center is active in this area through their Distributed Active Archive Center, which provides data to a number of the Cooperative Agreement Teams, and through their Remote Sensing Thrust Office.

- ◆ The Lewis Research Center is developing advanced communications satellites for data and information transmission.

- ◆ The Marshall Space Flight Center is working on the transfer of technology derived from communications and human space flight programs to the Chicago Fire Department to enhance fire fighter safety and communications capabilities.

Several interagency cooperative arrangements have been mentioned already. The following is a partial list of other NASA-interagency arrangements:

- ◆ USGS and Hawaii State Civil Defense plan to use orbital radar data and establish a Hawaii dense GPS array to mitigate volcanic disaster;
- ◆ NOAA, USGS—research and development leading to improved coastal zone hazard zonation;
- ◆ FEMA—national mitigation program;
- ◆ IAVCEI—decade program for study of hazardous volcanoes;
- ◆ Municipality of Scottsdale, Arizona—with OSAT and ARPA provide remote sensing aircraft overflights and assistance in processing/interpreting data; and
- ◆ The Program is also represented in the National Earthquake Program (16 participating federal agencies including NASA) with which it shares the goal of understanding earthquake mechanisms and regional to local vulnerability to seismic hazards.

G. Links to International Activities

The global nature of satellite observations and communications capabilities clearly leads to a responsibility to pursue natural disaster reduction from space for international humanitarian purposes. NASA's activities span a range of participation in planning and implementation activities with various international organizations.

Although significant issues related to national sovereignty and/or commercial copyrights may arise for the international use of remote sensing data, several major international programs warrant NASA's involvement. The best known international thrust, which NASA is committed to support through hazards research efforts already mentioned, is the United Nations International Decade for Natural Disaster Reduction (IDNDR).

The ReliefNet program, sponsored primarily by the U.S. Department of State and the United Nations Department of Humanitarian Affairs, and involving some 30 organizations promises to deliver a usable product for the international community. HazardNet project is another international effort spearheaded by researchers at Simon Fraser University (SFU) in Canada and supported by the National Weather Service and a number of U.S. universities. HazardNet is similar to ReliefNet (but much smaller in scope and level of international participations), but effectively provides access to a wealth of information and data sources through Internet. The Emergency Preparedness Information Exchange (EPIX) is a similar effort also led by SFU and now subsumed by HazardNet.

Recently, the Group of Seven (G7) Information Society launched the Global Emergency Management Information Network Initiative (GEMENI). This effort is still taking shape with the Canadians taking the lead. Should it materialize, it represents yet another Internet based information system development effort.

The U.S. Department of State Committee on International Science, Engineering and Technology (CISET) is currently considering establishing an international initiative on Disaster Assessment and Mitigation; NASA is involved in formative discussions currently underway.

Two major efforts sponsored by other space agencies warrant attention and perhaps the establishment of formal links thereto. The first is the planned Japanese Advanced Land Observation System (ALOS), a flight mission that includes disaster applications as a major objective. The European Space Agency is conducting an ambitious study on "Space Support to Natural and Technical Risk

Management," under the aegis of the Council of Europe, to assess how ESA assets can be employed for hazard mitigation and disaster relief in Europe. Their study plan is similar to that proposed by the MSFC GEOWARN team in late FY 1994. The results of the ESA study are expected in late August. The merging of ESA's activity with the proposed CEOS Working Group on Natural Hazards is currently under discussion (see below).

NASA is currently chairing a series of consultations with the managers of other national SAR satellite programs. The object is to develop an International SAR Satellite Fleet which would coordinate the various implementation plans without altering the charters of the individual agencies. NASA highest priority is the acquisition of high resolution SAR interferometry data to develop a global topographic data set and surface change detection. Other natural disaster-related applications include identification of flooded terrain (even through tree canopy) and monitoring of soil moisture conditions. The definition of a mutually acceptable data access policy will require lengthy negotiations, and it is unlikely that flight system changes pursuant to this coordination could be implemented before 2000, but the desire on the part of all participants is to reduce unwanted redundancy and improve return on investment in the flight projects.

NASA has numerous bilateral agreements for access to or exchange of satellite data. For example, the MOU between NASA and ESA regarding ERS-2 cooperation stipulates that natural disaster images will be conveyed in a timely way to NASA for research and response purposes. The characterization of Global Sea Level Change and of crustal deformation will draw on the extensive bilateral cooperative agreements (more than 45 countries) for exchange of space geodesy information.

Recently NASA has initiated discussion among CEOS members to create international convention for timely access to remote sensing data and communication during natural disasters.

V. Future Plans and Expected Accomplishments

NASA's substantial involvement in natural hazards research and disaster reduction will be more effective when carefully coordinated both within the agency, and with interagency and international collaborators. Natural disasters are a recurring threat to humanity and our progress in this field should go beyond Research and Analysis toward routine implementation for a tangible, recurring benefit to society.

The Office of Mission to Planet Earth has shown leadership in many aspects of natural disaster research and analysis and will continue to develop the most successful of these initiatives. However, NASA's ability to serve society in reducing natural disasters goes beyond the boundaries of Mission to Planet Earth. Future years' versions of this prospectus must be developed in increasingly closer coordination with other Offices within the agency.

Our initial emphases in research and applications will be in the areas described earlier: seismic hazard and regional consequences of short term climate variability (including aspects of flooding and sea level change). In addition an initial goal will be the transfer of robust technology to the responsible agencies. Transfer should be possible within three years in the area of wildfire sensors, and is designed into interagency letters of agreement under development for the long term operations of the GPS permanent array experiment in the Los Angeles Basin. This does not mean that NASA will be declare victory and close shop with respect to a specific natural hazard or technological approach, but it is our intent to design programs with lifetimes that phase out so that others may begin.

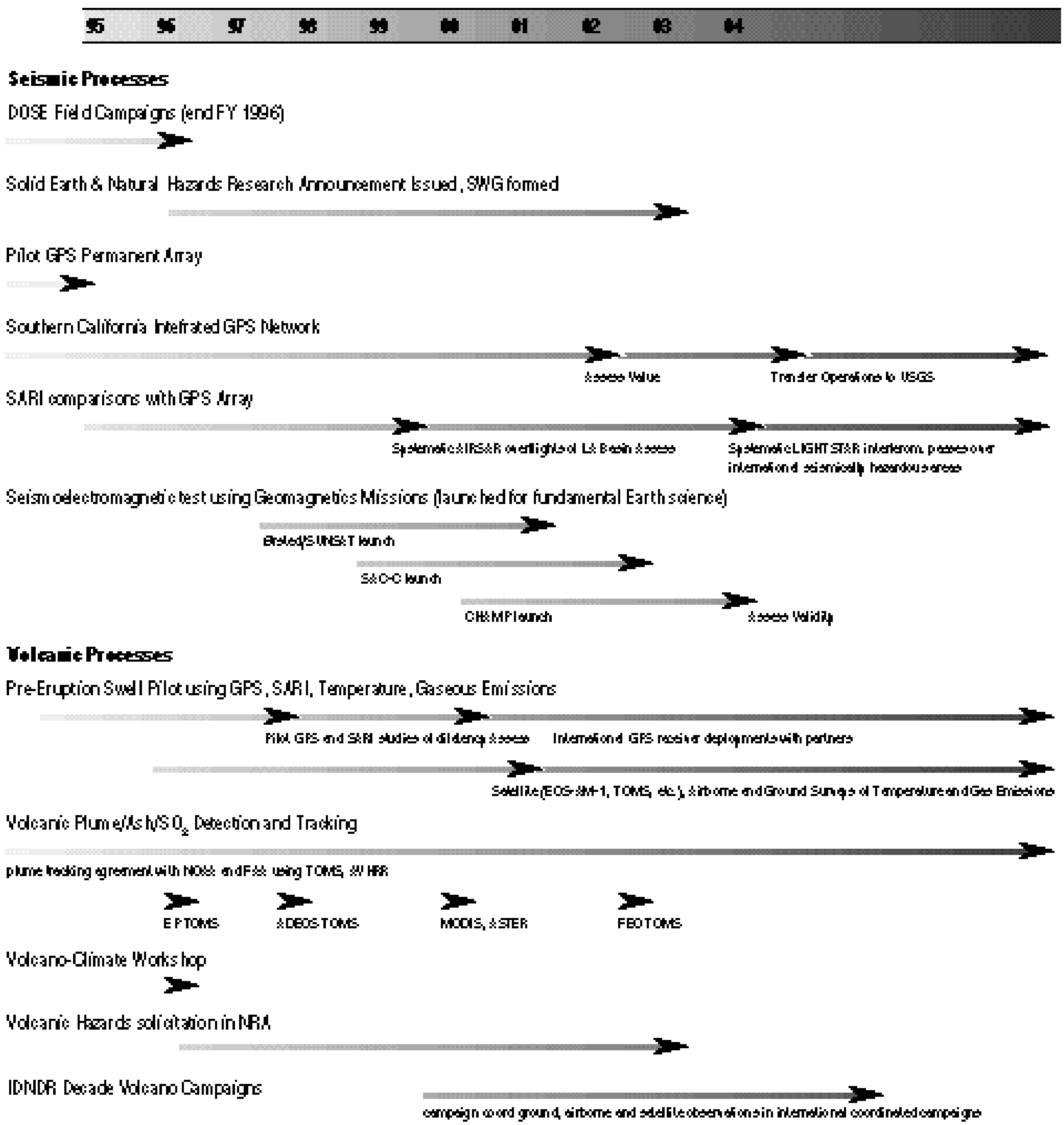
The Shuttle Radar Topography Mission (SRTM) will fly in 2000 and produce a global topographic data set within 12 months of flight. Techniques for factoring this global data set together with the complementary laser altimetry profile into risk assessments will be developed by the topography and surface change working group.

A multi-disciplinary Natural Hazards Research Announcement was issued in FY 1996. It reflects recommendations of the DOSE Science Team (October 1995 and previous discussions), Coastal Hazards Workshop (February 1996), Sea Level Change Workshop (November 1995), Floods Interagency Workshop (August 1995), Topography and Surface Change Science Team (May 1996), and the National Academy of Sciences Board on Natural Disasters and Committee on Environment and Natural Resources SubCommittee on Natural Disaster Reduction. Selections will be announced in early FY 1997.

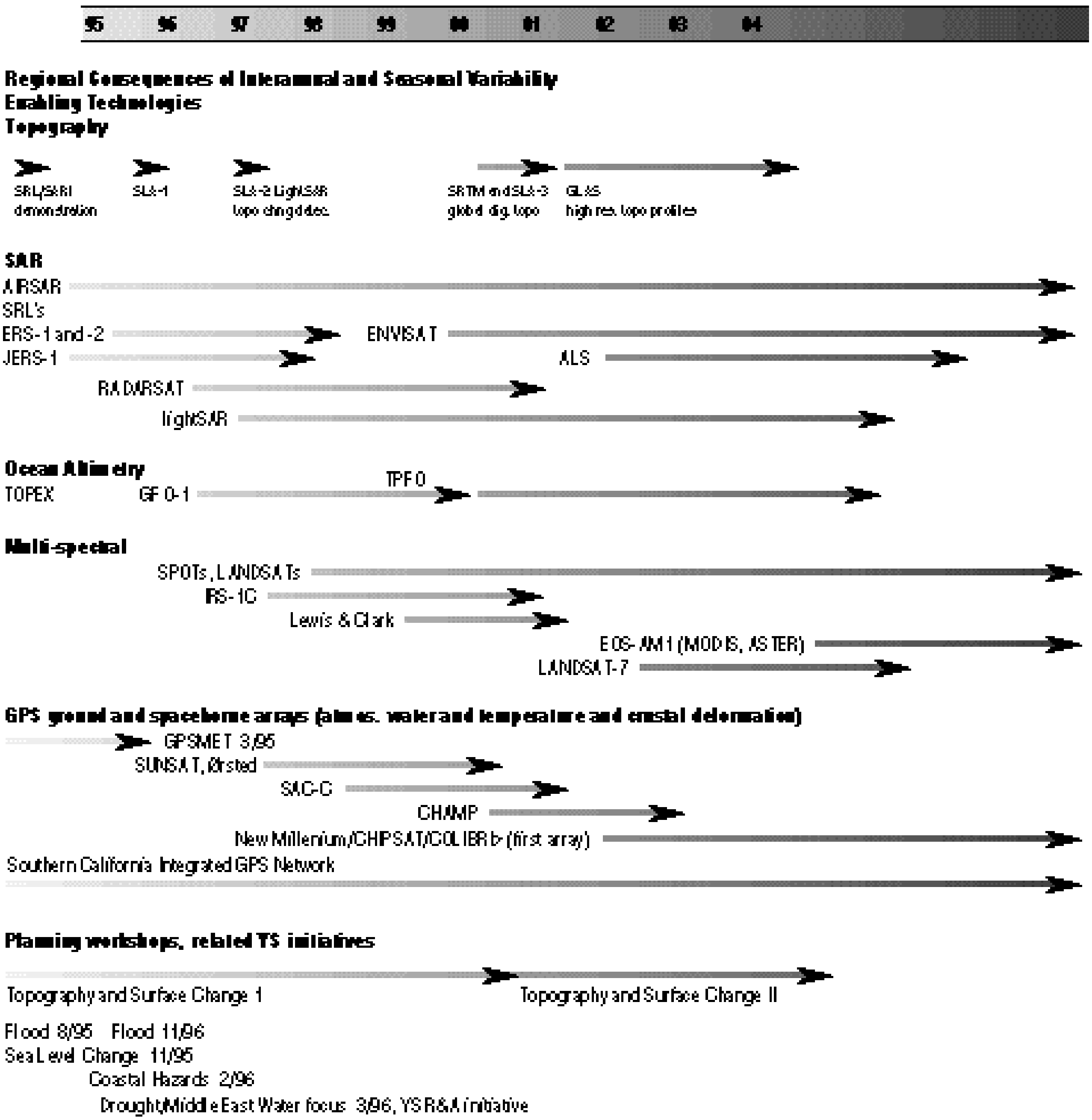
In parallel with research and technology development and transfer activities we will continue the broader dialogue within and external to NASA. The ad hoc working group on the use of the world's remote sensing capabilities for emergency response and relief formed under the Committee on Earth Observing Systems and is chaired by NASA. The focus of this group ultimately reduces to issues of timely exchange of readily usable data. Although the issues are complex, ranging from policy (e.g., emergency access to data restricted for commercial or security reasons) to compatibility of format, avenues of information transfer, conventions for ready interpretation, etc., there is a growing sense of international motivation. The international will exists to use our hard-earned, state-of-the-art technology for the fundamentally basic application of protecting lives and property from the extremes of nature.

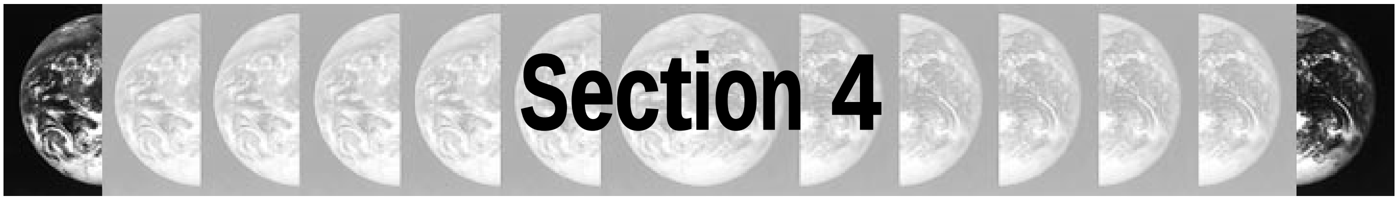
This is the first version of a living document. Several NASA Offices in addition to Mission to Planet Earth which currently support aspects of natural disaster reduction can contribute to a coordinated agency-wide Natural Disaster Reduction Program: Space Access and Technology, Management Systems and Facilities, Life Sciences, and Space Communications. There exist dozens of tasks undertaken at various NASA centers and universities. Because NASA's ability to serve society in reducing natural disasters goes well beyond the boundaries of MPTE, the preparation of future versions of this prospectus will involve increasingly closer coordination with other NASA Offices.

Natural Hazards



Natural Hazards





Section 4

Long-Term Climate: Natural Variability and Change Research

EXECUTIVE SUMMARY

This section outlines NASA's contribution to broader national and international efforts to understand the causes and impacts of long-term (decades-to-centuries) variations in the climate system. Long-term climate variability encompasses changes of regional-to-global scale climate, both natural and human-induced, that occur over periods longer than a few years. NASA's objective is to make key contributions to a wider interdisciplinary effort involving other U.S. agencies and institutions, as well as other countries. This larger effort addresses the broad scientific agenda of the U.S. Global Change Research Program (USGCRP) at the national level, and the World Climate Research Program (WCRP), the International Geosphere-Biosphere Program (IGBP) and the Intergovernmental Panel on Climate Change (IPCC) at the international level.

Assessing the potential impacts of climate change requires the observation and analysis of on-going variations in present climate and their impacts on the environment, in order to improve the understanding of climate processes to the point where useful predictions of regional climate change can be made. This enhanced understanding will enable the early detection of climate trends, the separation of natural variability from forced climate changes, the quantification of sources and sinks of greenhouse gases, the determination of the main climate feedback processes, and diagnosis of the thermal energy, water, ozone, and carbon cycles that couple the main components of the climate system. Key scientific questions are as follows:

- What is the observational evidence for trends in the climate mean-state and variability?
- What are the primary mechanisms of climate system variability?
- What are the causes of uncertainty in climate change predictions?

Accordingly, NASA Mission to Planet Earth (MTPE) research objectives associated with the long-term climate issue are:

1. To characterize and document long-term climate variability and trends through systematic global observations of the climate system and its external forcings;

2. To understand the nature of key climate-forming and regulating parameters, and to identify the causal factors of observed climate variations and feedback processes that govern the response of the climate system; and

3. To assess the predictable aspects of long-term climate variability and changes, including regional impacts, through the combined application of observations and global models.

A comprehensive research program that addresses these objectives should encompass the capability to measure key climate parameters, a strong field observation and data analysis program to improve knowledge of key processes, an active climate modeling program to develop predictive capability for regional climate change, and an integrative analysis program to develop methods for impact assessments (Fig. 4-1). The MTPE Science Program contributes to each of these elements through its primary responsibilities in satellite data assembly and analysis programs, through modeling studies, and multi-disciplinary research and analysis projects supported by field campaigns and experiments. The principal priorities of the MTPE program addressed in this plan are:

◆ **Global Satellite Observations**—including the NASA/NOAA Pathfinder and other ongoing data analysis projects, the Earth Observing System (EOS) program, Earth System Science Pathfinders (ESSP) small research satellite missions, multi-agency planning for the National Polar Orbiting Operational Environmental Satellite System (NPOESS),

◆ **Process Studies and Field Campaigns**—ground-based and airborne *in situ* measurements planned and implemented by the basic MTPE Science Discipline Programs under the Research and Analysis (R&A) Program; and

◆ **Modeling Studies**—including data assimilation, climate diagnostics, model improvements through organized community intercomparisons, observing system simulation experiments; and prediction/assessment runs.

The NASA program builds on a research infrastructure developed over the past three decades through a partnership with other Federal agencies and the university community, and seeks to maintain the flexibility to respond to new, challenging scientific issues as they emerge. It is clear, however, that the implementation of scientific priorities must reflect budget realities. Consequently, in the current fiscal environment, some important research tasks must be either delayed or deferred to other agencies.

Although this component of NASA research addresses specific climate science issues identified by the USGCRP, the results will contribute to progress in the broader field of Earth system science, including the issues recognized by the National Science and Technology Council's (NSTC) Committee on Environment and Natural Resources (CENR), such as natural disaster reduction, air and water quality, biodiversity, and ecology.

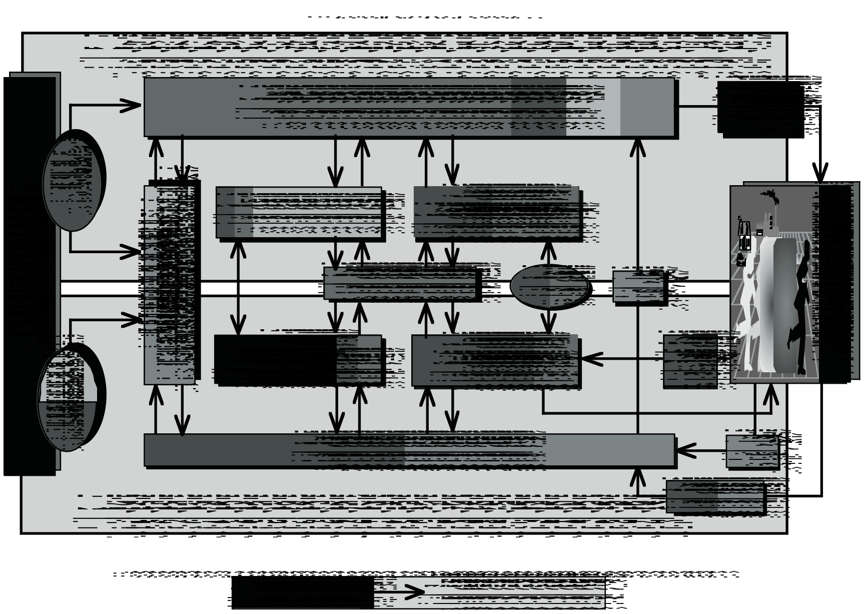


Fig. 4-1: Integrated model of the Earth system for decadal climate prediction (NASA)

The deliverable products of this worldwide effort are improved global observations, better understanding of transient decadal (or longer period) climate variations and the factors that determine the sensitivity of climate to external forcings, numerical simulations and scientific assessments of global and regional climate variability or trends, and the evaluation of their impacts on society. For example, as clearly stated by the IPCC in its 1990 report on Climate Change Response Strategies, "There are many uncertainties in our predictions particularly with regard to the timing, magnitude, and regional patterns of climate change. Ecosystems affect climate, and will be affected by increasing carbon dioxide concentrations. Rapid changes in climate will change the composition of ecosystems; some species will benefit while others will be unable to migrate or adapt fast enough and may become extinct. Enhanced levels of carbon dioxide may increase productivity and efficiency of water use in vegetation. In many cases, the impacts will be felt most severely by regions already under stress, mainly the developing countries. The most vulnerable human settlements are those exposed to natural hazards, e.g., coastal or river flooding, severe drought, land-slides, severe storms and tropical cyclones. Developing countries are particularly vulnerable to the adverse consequences of climate change because of limited access to the necessary information, infrastructure, and human and financial resources."

Furthermore, as noted in the IPCC Climate Change 1995 report on Impacts, Adaptations and Mitigation of Climate Change, assessing potential regional impacts of climate change depends on our ability to resolve issues such as how sensitive, adaptable, and vulnerable is a particular system to climate change. The broad research addressed by the five major themes of this MTPE Science Research Plan should help provide policy makers with timely information which are essential to establishing the scientific basis for strategic global change decisions affecting society.

◆ ◆ ◆

1. Introduction

This research program derives from the recognition that human activities are causing changes of the land use and atmospheric composition that are capable of changing climate and inducing significant impacts on energy utilization, agriculture, natural ecosystems, water availability, water quality, and sea level. Alteration of the land surface modifies the energy-water-vegetation interaction at the land-atmosphere interface. Model studies indicate that changes in the surface energy and moisture budgets can alter regional climates, while increases in atmospheric aerosol and carbon dioxide and other greenhouse gases influence the global energy budget and will affect global climate over decadal and longer time scales. The IPCC's Climate Change Report concluded that "the balance of evidence suggests a discernable human influence on global climate."

Policy-relevant objectives of scientific research on long-term climate variability and change include:

- Development of plausible scenarios for regional climate and ecosystem changes, suitable for assessing economic and societal impacts of such changes;

- Improving estimates of the global warming potential of various gases and aerosols in the atmosphere, including interactions with other chemical species;

- Improving the ability to determine the regional sources and sinks for atmospheric carbon dioxide, as part of the monitoring system for greenhouse gas emissions reduction agreement;

- Reduction of the range of uncertainties in predicting the rate and magnitude of global warming over the next century based on a better understanding of clouds, aerosols and their impact on the Earth radiation budget, heat transport and storage by the ocean, sea-ice processes and the formation of deep oceanic waters;

- Prediction of anthropogenic changes in regional climate and the range of natural climate variability on decadal-to-centennial time scales;

- Objective diagnostics of global warming induced by greenhouse gases, and documentation of other climatologically-significant natural changes in the global environment; and

- Improved understanding of the interactions of human societies with the global environment, enabling quantitative analyses of existing and anticipated patterns of change.

2. Background

The issue of global warming is adopted as a useful paradigm for studies of decadal-to-centennial climate variations as it encompasses the widest range of physical and chemical processes and the dynamics of the full interactive global climate system, including the atmosphere, oceans, cryosphere

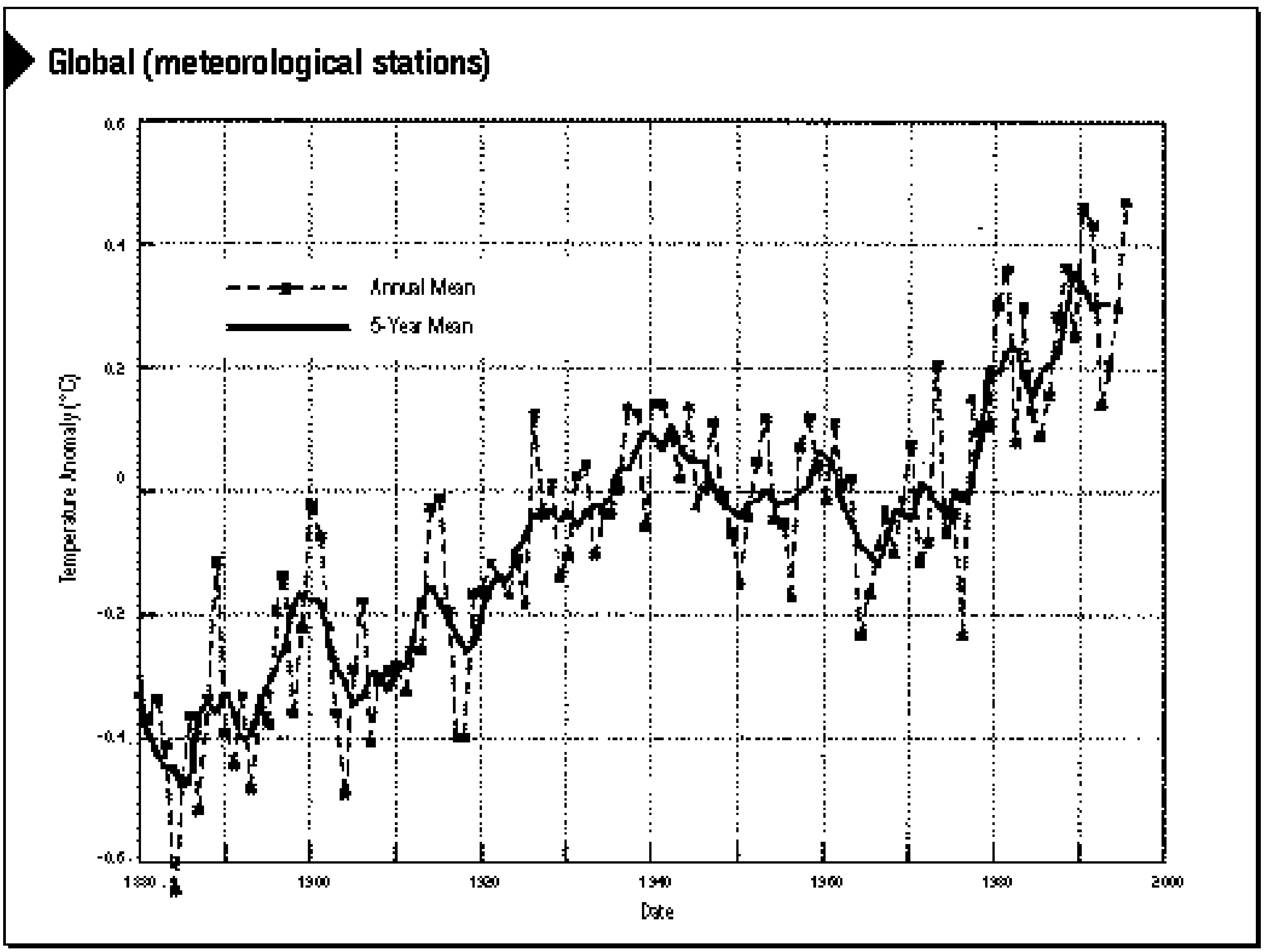


Fig4-2

and land surface. The detection of global warming is the subject of considerable debate, as the observations over the last 100 years are insufficient to unambiguously separate long-term natural variability from human-induced trends (Fig. 4-2). Consequently, assessments of future climate changes are dependent upon climate model predictions. State-of-the-art general circulation models predict a global warming between 1.5°C and 4.5°C and substantial changes in precipitation and evaporation for a doubling of atmospheric carbon dioxide concentration. A climate change of this magnitude would have significant impact on energy utilization, agriculture (drought and floods), natural ecosystems, water resource availability, water quality, and eventually, sea level. But the potential impact of a 1.5°C warming is very different from that of a 4.5°C warming. Predicting quantitatively the magnitude and rate of global climate change is the scientific basis of strategies for achieving sustainable development at national and international scales.

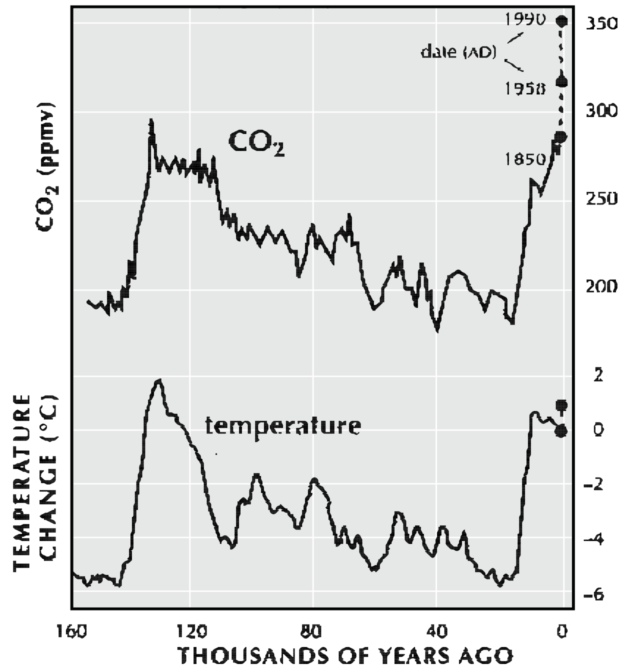


Fig 4-3

Clearly, a full understanding of long-term climate change involves scientific issues beyond the programmatic scope of NASA research alone. The present plan focuses essentially on NASA scientific research priorities.

2.1 Current Scientific Issues

CHARACTERIZATION: *What is the observational evidence for long-term variability of climate parameters, change in forcing factors, feedback processes and key diagnostic properties?*

Energy Cycle:
Solar radiation, absorbed and stored as heat by the ocean and atmosphere, drives the Earth's energy cycle. The stored energy is redistributed from equatorial to polar regions through oceanic and atmospheric transports of comparable magnitude. A global surface warming of about 0.5°C occurred over the past century. This trend is superimposed on significant natural variations resulting in periods of cooling or no change, as observed during the satellite record of the past 15 years. During this time there was little change of tropospheric temperature rather cooling of the stratosphere. The existence of a warming trend during the last century is supported by analysis of temperature profiles in glacier boreholes, as well as the widespread retreat of snowlines and glaciers in alpine regions. Proxy temperature information from ice cores suggest that a general cooling existed over the past several thousand years, prior to the recent warming of the past century (Fig. 4-3).

A significant gap in our understanding is associated with unknowns in the role and variability of the oceans, which become more significant as time-scales increase. The deep ocean circulation, strongly linked to surface processes in the polar regions, only shows considerable variability over decadal time scales. Historical data from the North Atlantic

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Fig. 4-2 (left): Global surface air temperature (Hansen)

Fig. 4-3 (above right): CO_2 and temperature records from antarctic ice cores over the past 160,000 years, and recent atmospheric measurements

indicate variability in sea-ice coverage and oceanic temperature and salinity on decadal and longer time scales. The sea surface temperature in the northwest Atlantic is well-correlated with the atmospheric surface temperature averaged over the Northern Hemisphere. Sea surface temperature anomalies in the central tropical Pacific, which drive the ENSO, have also been found to be a major influence on the atmospheric circulation and temperature on decadal and longer time scales. However, even though the ocean is known to play a major role in the long-term climate, the energy budget of the upper ocean and deep ocean temperature trends are still largely unknown.

A major uncertainty in atmospheric forcing of the ocean is associated with the partitioning of radiant energy by clouds between the ocean, atmosphere and space (Fig 4-4). The precise effects of cloud feedbacks are not known, but there is some preliminary evidence of cloud cover variability over the past several decades. Changes in several climate forcing factors are well documented during the past 15 years, such as increased abundances of certain greenhouse

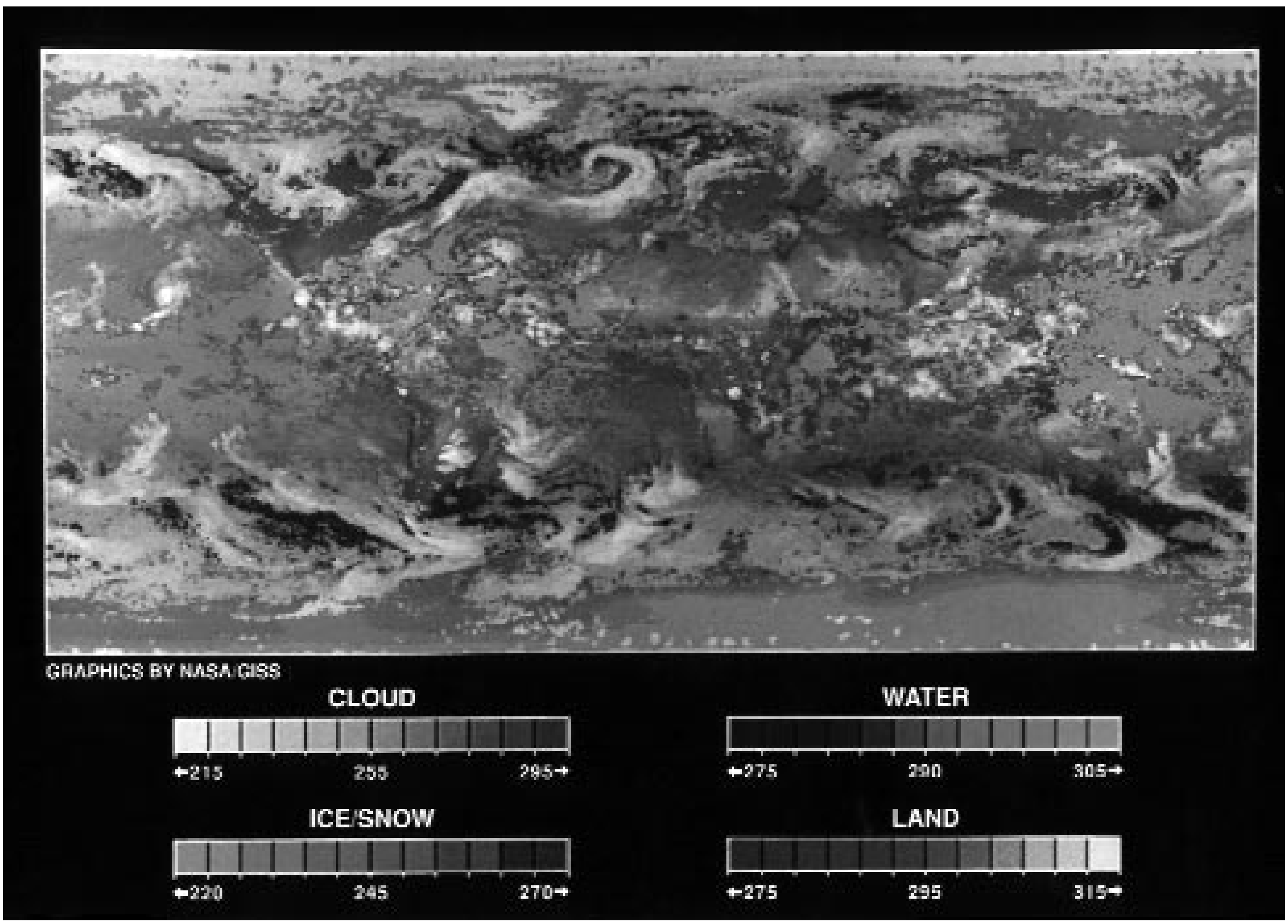

Fig. 4-4: ISCCP world cloud cover patterns (Rossow)

gases, decreases in stratospheric ozone, small variations in solar irradiance, and changes in vegetation cover. On the other hand, the global distribution of water vapor, the most important greenhouse gas, is poorly known. There may have been important changes in tropospheric aerosols, but these are not well documented.

Water Cycle:

Trends and changing patterns in precipitation are fundamentally important for human habitation and agriculture. Atmospheric circulation and cloud processes control the balance of precipitation and evaporation that, together with land hydrological processes, determine water supply. There are hints of a recent increase of moisture within the tropical troposphere and midlatitude stratosphere, and increase (decrease) in precipitation at temperate and polar (subtropical) latitudes. Proxy climate indicators, including pollen types and tree rings, reveal regional fluctuations in drought frequency during past centuries and millennia. In the past century, sea level has risen faster than expected from thermal expansion alone. Alpine glaciers have retreated overall, but the mass balance of major ice sheets is largely unknown. The extent of sea ice has fluctuated significantly during the relatively brief period of satellite microwave observations (1979–present) but no significant overall trend has yet been observed. Recent reports suggest a small retreat of sea ice in the Northern Hemisphere. Significant transient variations in the salinity of the superficial and intermediate North Atlantic ocean waters have been observed over the recent period. This may be modulated by the changes in surface salinity in the sub-polar North Atlantic through changes in fresh water runoff from the Arctic. In the tropics, rainfall can modify the buoyancy and heat balance of western Pacific surface waters and thereby influence the oceanic response to climate anomalies originating from that region

Carbon Cycle:

Chemical and biological cycles determine the composition of the atmosphere; especially the amounts of various trace constituents that can alter climate. Abundances of several greenhouse gases have been rising for at least the past century; today's abundances are significantly higher than those found in ice cores for the past few centuries. Recent variations in the rates of change of change of CH_4, CO_2 and N_2O have no quantitative explanation. The rate of increase of atmospheric CO_2 is about half the emission rate from human activities and the carbon budget has yet to be fully determined. The rate of CH_4 increase is consistent with estimated sources from a combination of human activities, but many features of CH_4 chemistry in the atmosphere and cycling in the biosphere are poorly known. In general, the relative roles of the ocean and land biosphere in regulating carbon are poorly known. However, inter-decadal variations in the epipelagic ecosystem of the central North Pacific ocean which appear to be related to long-period atmospheric and associated oceanic fluctuations, may indicate long-term variations in total oceanic organic carbon over large areas.

Ozone Cycle:

Changes of ozone abundance constitute a particularly complex and poorly understood climate forcing factor on account of the sensitivity of the ozone greenhouse effect to changes in vertical profile. It is estimated that increase in tropospheric ozone during the past century caused a positive climate forcing of about 0.4 W/m^2, with an uncertainty of a factor 2. The recent decrease in lower stratospheric ozone may have caused a negative forcing ranging from -0.1 to -0.2 W/m^2. A better characterization of the vertical distribution of ozone change is required, along with realistic three-dimensional climate simulations, in order to assess the role of ozone in climate change. (Science issues relevant to ozone chemistry are discussed in the Atmospheric Ozone Research Section of this plan).

Changes in forcing factors:

On time scales longer than about one to two decades, how solar forcing or land surface albedo have changed is not known. In addition, there are other poorly defined forc-

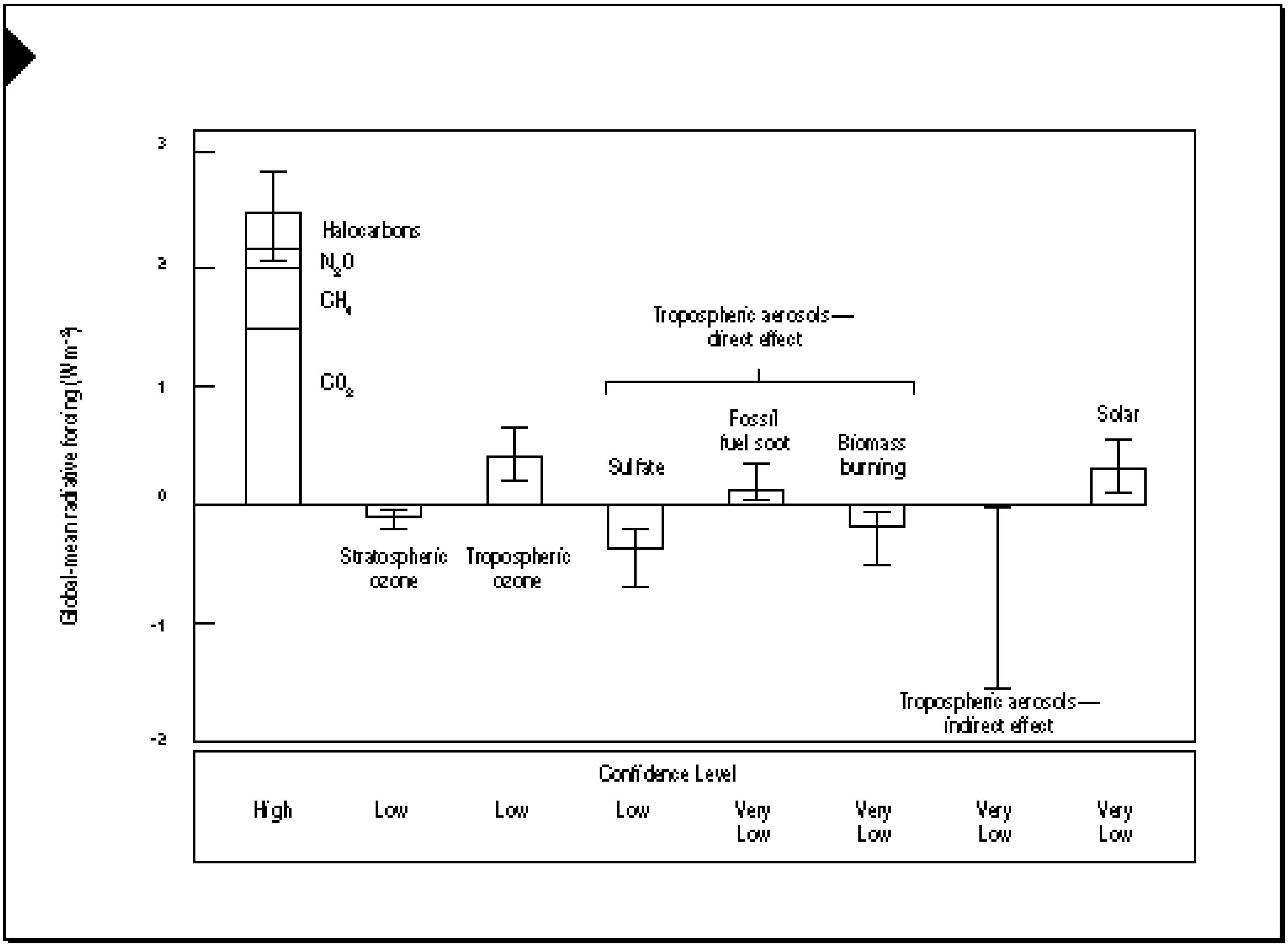

Fig. 4-5: Estimates of globally and annually averaged radiative forcing (IPCC 1995)

ings of the global energy balance, which all operate by changing the amount or spectral distribution of radiation at the top of the atmosphere and radiation flux divergence in the atmospheric column. Forcing by tropospheric aerosols and ozone change are very poorly determined due to inadequacies in existing measurements. CO_2 and CH_4 abundances are well measured, but it is difficult to predict future amounts because carbon fluxes among the land-atmosphere-ocean sources and sinks on these time scales are unknown globally (Fig. 4-5).

UNDERSTANDING: *What are the possible causes of long-term climate change and the sensitivity of climate?*

Natural variability versus forced changes:
The magnitude, characteristic time scales and causes of natural climate variability are not known, nor are the roles played by the ocean, biosphere and ice sheets; but

there are indications of internally-generated ocean variability on decadal to century time periods. International research programs (CLIVAR/GOALS and CLIVAR/DECCEN) have launched studies to investigate the processes that couple the ocean and atmosphere that can cause transient climate variations on a broad spectrum of time scales. IGBP is considering interactions between the biosphere and physical climate factors that may cause important changes over somewhat longer times. These programs must be supplemented by long-term monitoring of climate forcing factors and key diagnostics, and by analysis of these data to help identify the processes causing natural climate variations. Identifying a forced change requires a long data record to distinguish transient natural variability from forced variations.

Climate sensitivity:
Comparisons of climate model simulations with the past century temperature record or paleoclimatic indicators of past changes do not lead to precise estimates of climate sensitivity to external forcing, because concomitant variations in climate-forcing factors are inadequately documented. Current empirical estimates of climate sensitivity, as indicated in the IPCC assessments, are within the range of climate model simulations: estimates of global temperature change in response to a doubling of CO_2 range between 1.5°C and 4.5°C.

Inadequately known feedback processes:
The key feedback processes operate by changing the net amount and spectral distribution of radiation at the top of the atmosphere. Even the sign of the net cloud feedbacks on long-term climate change is not known, nor the indirect effect of aerosol-induced changes in cloud optical properties. Water vapor feedback is, by comparison, well-known, yet its uncertainties are significant. Trace gas feedbacks involving the carbon cycle and the biosphere are not well understood. Sea ice feedback is potentially large, but uncertain in magnitude, and there may be important sea ice/cloud interactions. Ocean dynamics, such as variations in meridional overturning, can produce major feedbacks on climate, but the sensitivities and time scales of these effects are unknown. The exchanges of heat and water at the air-sea interface control a key feedback loop between the atmospheric and oceanic circulations. Since the atmospheric circulation loses the memory of its initial state within about two weeks, strong ocean coupling is necessary to maintain climate inertia. Other feedbacks involve atmosphere-land surface fluxes.

Persistent forcing can build up many additional climate feedback processes, requiring models that couple the various components of the climate system: ocean, atmosphere, cryosphere, lithosphere, land hydrological system, and biosphere. Uncertainties in model representations of these interacting systems limit present ability to estimate the climate response. Current model simulations of a 2 x CO_2 climate consistently show continental drying in midlatitudes and increased soil moisture at higher latitudes with global warming, but the validity of this prediction is highly uncertain. Model sensitivities in paleoclimate simulations can also be usefully compared with paleoclimate data. Significant discrepancies exist in simulations of climate changes in both the tropics and polar regions.

PREDICTION AND ASSESSMENT: *What aspects of long-term climate are predictable?*

Transient climate forcings:
The eruption of Mount Pinatubo is an example of a transient climate forcing of sufficient magnitude to cause a noticeable response but short enough duration to exclude a long-term direct impact on climate, although short-term forcing may excite long-lived modes. In this case, the transient climate response is determined by the direct radiative effect of volcanic aerosol dispersed in the atmosphere and various feedbacks within the atmosphere. Current atmospheric general circulation model (GCM) simulations appear to reproduce fairly realistically the global response to this forcing. More events of this kind need to be documented by

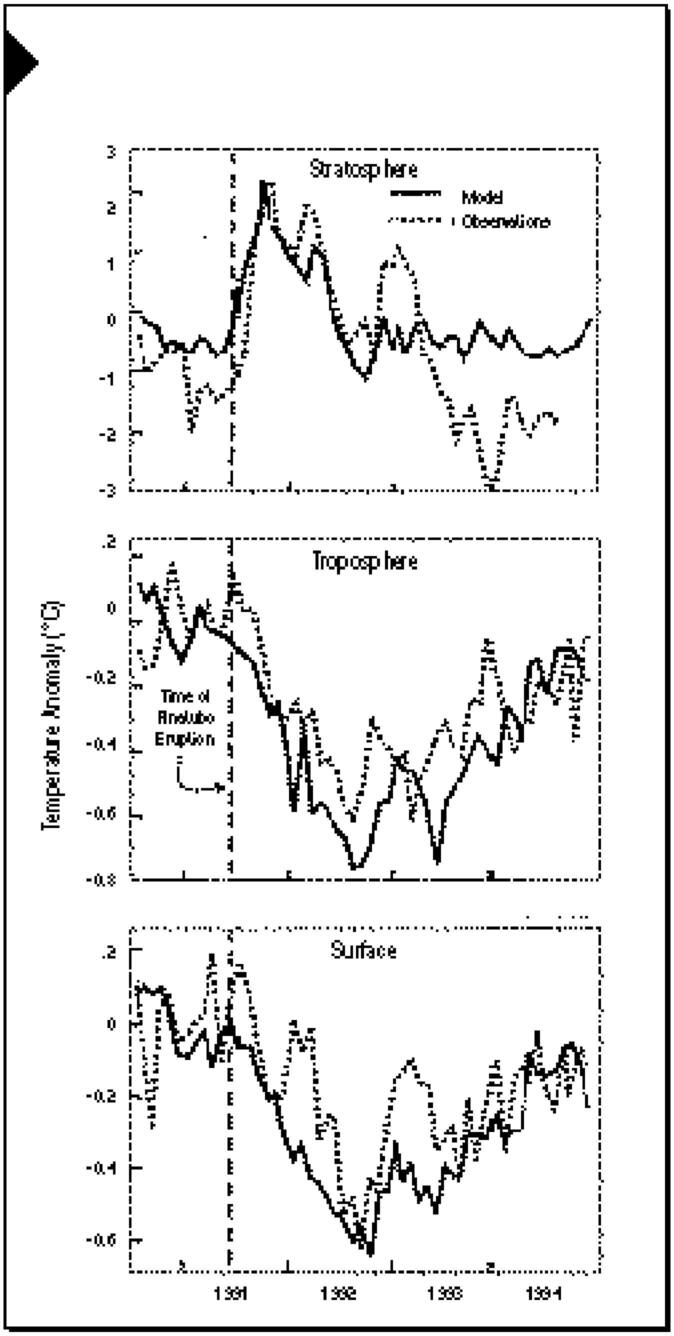

Fig4-6

Fig. 4-6: Comparison of climate model predictions after the eruption of Mt. Pinatubo in 1991 (Hansen).

comprehensive observations to enhance the confidence in GCM results (Fig. 4-6).

Predicting anthropogenic forcings:
Our ability to predict future human activities and the changes they induce, such as gas emissions or production of aerosols also has limitations. Large variations have occurred during the past decade in the growth rates of several greenhouse gases, especially methane, which are not well understood. Even the budget of CO_2 is known with considerable quantitative uncertainty. Space and *in situ* sampling programs are needed to assess potential sources of key chemical composition changes in the troposphere and stratosphere.

Regional climate impacts:
Applying climate change assessments to practical regional environmental impact management requires firstly disaggregating global or large scale predictions to regional scales, and further applying the products to detailed agricultural, ecological or economic forecasts. Quantitative representations of land surface, soil and vegetation properties are essential for this process. Regional climate changes may be largely unpredictable, except in a statistical sense: this constitute another methodological difficulty that requires special attention in order to achieve the desired practical benefits.

2.2 NASA Research Strategy

Explaining the causes of long-term climate variability requires measurement of all significant climate forcings and quantification of feedbacks and internal exchanges of energy, water, and carbon. Determination of the heat and water transports in the atmosphere requires three-dimensional wind measurements that resolve all relevant scales of motion. Determination of the heat and salt transports by the ocean circulation requires measurements of three-dimensional velocity fields that also resolve energy-containing dynamical scales. Achieving these goals worldwide is beyond current observing capabilities. However, interpretations of climate changes could be constrained by accurate estimates of global climate forcings and radiative fluxes, together with key diagnostic parameters such as temperature, water distribution and precipitation. This more limited monitoring objective still requires national and international cooperation in the framework of an integrated global observing stategy. This is particularly true in the current NASA budget environment.

GLOBAL CHARACTERIZATION: *To characterize and document long-term climate variability and trends through global observations of the climate system and its external forcings.*

◆ Continue and improve existing time-series of important environmental measurements:

– *Atmosphere*—solar irradiance, stratospheric aerosols, total ozone and vertical profiles, lower troposphere water vapor, cloud radiative properties, temperature
– *Ocean*—upper layer surface temperature, sea-level topography, surface fluxes
– *Land surface*—vegetation cover and properties
– *Cryosphere*—extent and concentration of sea ice, extent of the continental snow cover

◆ Implement key missing or inadequately sampled observations:

– *Atmosphere*—water vapor profiles in upper troposphere and lower stratosphere, tropospheric aerosol properties, evaporation
– *Ocean*—surface wind stress
– *Land surface*—surface temperature, evaporation
– *Cryosphere*—ice sheet topography

◆ Develop new technologies for other key missing observations:

– *Atmosphere*—precipitation, three-dimensional winds, cloud microphysical properties and three-dimensional structure
– *Ocean*—surface salinity, surface heat flux
– *Land surface*—soil moisture, evaporation and heat flux
– *Cryosphere*—snow amount or depth, sea ice thickness

UNDERSTANDING: *To understand the nature of key climate-forming and regulating parameters, identifying the causal factors of observed climate variations and the feedbacks that govern the response of the climate system.*

◆ Analyze the available global satellite database covering the era from 1979 to present, supplemented by conventional datasets:

– There is already a 15+ year record that will be extended to three decades by 2009, the end of the second "Understand" period in the MTPE Strategic Plan roadmap. Analysis of these data is already underway as part of several NASA contributions to the World Climate Research Program (ISCCP, SRB, GVAP), and as part of the NASA/NOAA Pathfinder Project. This database can be used now to constrain explanations for observed climatic changes during the recent period. This activity will serve as a prototype of the needed research and identify deficiencies in current observations. In addition, it is also important to further develop historical and paleoclimatic records to supplement current observations as climate model tests.

– Evaluate the realism and accuracy of simulations of climate forcings by aerosols, gases and other radiative mechanisms.

– Evaluate the realism of convection/cloud generation schemes to improve prediction of precipitation, water vapor, and cloud feedbacks.

- In parallel, conduct experimental field campaigns targeted on key climate system processes:

PREDICTION AND ASSESSMENT: *To assess the predictable aspects of long-term climate variability and change, including regional impacts, through the combined application of observations and global models.*

- Based on model simulation experiments, identify the key climate system variables that need to be determined from observations to serve as initial values for climate predictions.

- To complement observations of forcings and feedbacks, the following modeling improvements are among the highest priority:

– Improve model representations of ocean surface topography and ocean physics and biogeochemistry, including improved mixing parameterizations, so that realistic water mass formation and transports of heat, salt and carbon are achieved, and evaluate the accuracy of ocean data assimilation schemes.

– Develop improved ice sheet dynamics models to characterize polar ice sheet responses to climate changes.

– Improve coupled atmosphere/ocean/ice models to reduce the need for heat/ freshwater/ momentum flux corrections.

– Improve treatment of water in all phases in land hydrological models, ecosystem models and economic models, to better characterize future changes in water availability.

– Develop coupled three-dimensional chemistry-climate models with an ocean tracer component, coupled to the ecosystem, to simulate future changes in trace gas concentrations.

– Assemble complete Earth system model (through coordination with the Integrative Modeling and Assessment program of the USGCRP).

The strategy should begin with the best existing models of each component, but expand their capacities in several directions by improving the realism of ocean, chemistry, biology and human interactions. Given expected increases in computing power it is realistic to assume that a coupled troposphere/middle atmosphere model, with a dynamic ocean and land surface/ecosystem model included, could be running successfully within a decade. Cross-model comparisons and improvements among climate, impact and economic modelers should be encouraged to obtain consistency and mutual understanding of the proper uses/limitations of each modeling effort. At all stages there should be comparisons of models with the global datasets being assembled, including paleoclimate datasets.

3. NASA Program Elements

A comprehensive research program on decadal-to-centennial climate change is based on four major components: a capability for accurate monitoring of climate properties, a strong measurement and data analysis program to improve knowledge of key forcing and feedback processes, a strong modeling program to develop predictive capability for global and regional climate change and an integrative program to develop impact assessments. NASA's Mission to Planet Earth contributes to each of these elements through the acquisition and analysis of satellite data, a modeling effort and research supported by field experiments.

3.1 Global Satellite Observations

Analysis of the 15-year record of meteorological satellite data, supplemented by data from NASA experimental satellite missions, is proceeding through the NASA/NOAA Pathfinder program. The first keystone AM-1 and PM-1 missions of Earth Observing System (EOS) are underway, together with UARS and TOPEX/ POSEIDON. Within the next few years, the TRMM, NSCAT and SEAWIFS systems will be launched. A new program of smaller experimental spacecraft, Earth System Science Pathfinders (ESSP), will supplement the main EOS satellites.

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) offers an effective, and possibly the only realistic opportunity to ensure the continuity of basic global meteorological and climate measurements. NPOESS is the common system that will replace the DOD's Defense Meteorological Satellite System (DMSP) and NOAA's Polar-orbiting Operational Environmental Satellite (POES). The planned launch of the first NPOESS platform will be around the year 2007. Interagency planning is underway to identify common areas of interest and operational requirements, as well as climate science monitoring requirements. The principal issue to be addressed by NASA concerning the development of the first NPOESS series is the commitment to provide improved temperature and

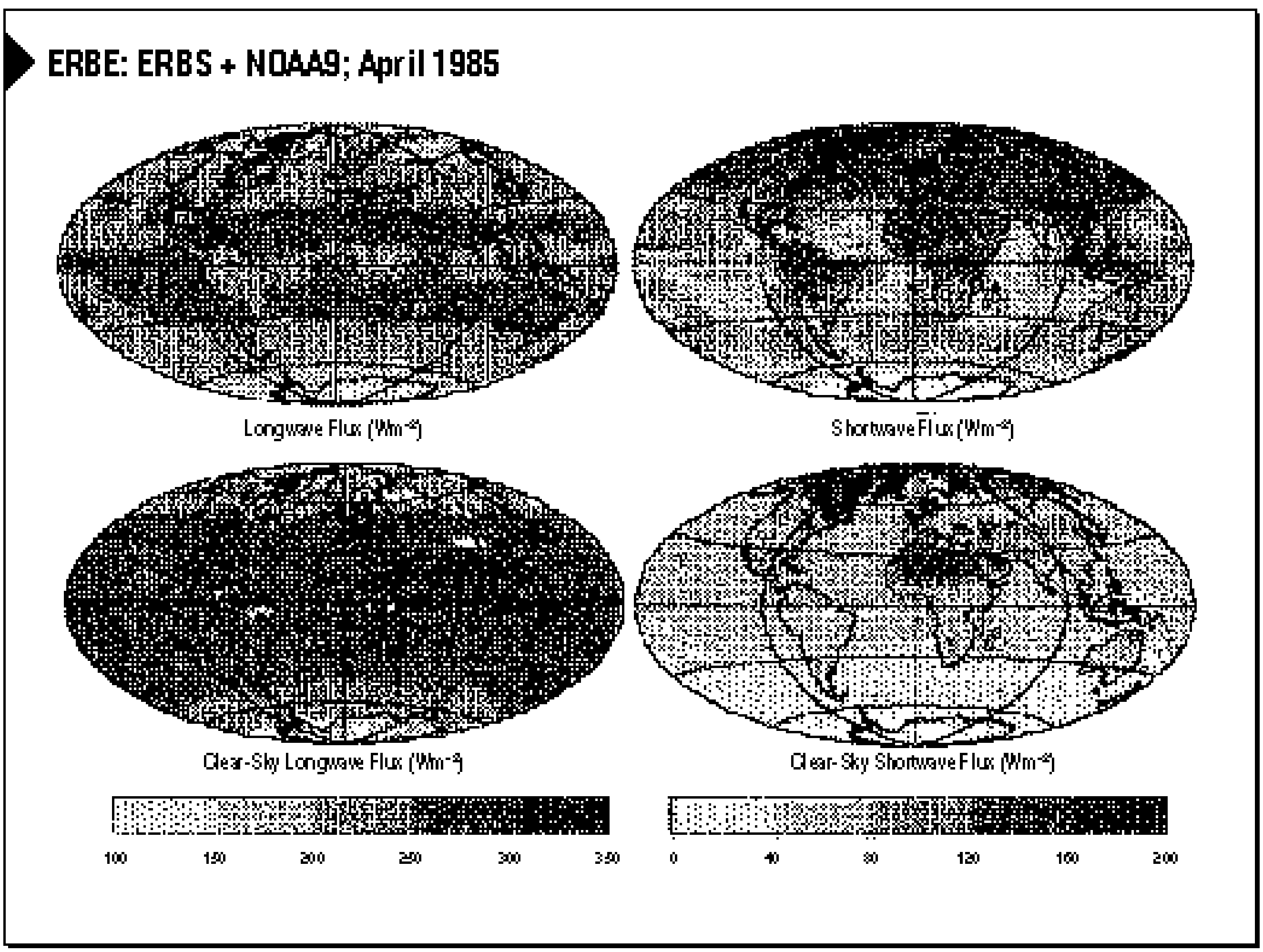

Fig 4-7

Fig. 4-7: Radiation budget from the NAA Earth Radiation Budget Experiment (ERBE)

moisture sounding capability (i.e., 1°C accuracy and 1 km vertical resolution) required both for improvement in numerical weather prediction skill and climate monitoring. Specific MTPE program elements include:

◆ **Pathfinder and Other Ongoing Analyses:**

– *Atmosphere:* Processing of existing datasets from civilian and military meteorological satellites is providing information about clouds (ISCCP), atmospheric temperature and humidity (from HIRS/MSU), ozone (TOMS, SBUV), and precipitation (SSM/I and imagery). Ongoing analyses of ERBE and SAGE continue to improve understanding of Earth radiation budget and clouds (Fig. 4-7), as well as stratospheric ozone, water vapor and aerosols. Surface wind fields from SSM/I and ERS-1, 2 scatterometers provide improved atmospheric forcing estimates for ocean studies.

– *Ocean:* Sea surface temperature datasets are being produced from 1982 onwards (AVHRR)(Fig. 4-8). Large scale circulation features can be obtained from consistently processed sea level measurements provided by GEOSAT, TOPEX/POSEIDON, and ERS-1, 2 altimeters; ocean color from CZCS.

– *Land:* Analysis of LANDSAT data remains the primary data source, but experimental SAR datasets are becoming available.

– *Cryosphere:* SSM/I provides information about sea ice cover and concentration continuing the record started by ESMR and SMMR on NASA experimental Nimbus satellites (Fig. 4-9). SARs provide measurements of sea ice dynamics.

– *Chemistry:* The UARS mission is providing a detailed look at stratospheric ozone chemistry. SAGE supplements some of these measurements with profiles of ozone, water vapor and aerosols (Fig. 4-10).

Fig. 4-8 (below): Global sea surface temperature (NASA)

Fig. 4-9 (center): Nimbus-7 ocean ice maps (NASA)

Fig. 4-10 (opposite): Sage II derived total atmospheric water vapor between approximately 9 km and 16 km—June through August, 1986–1988 (McCormick)

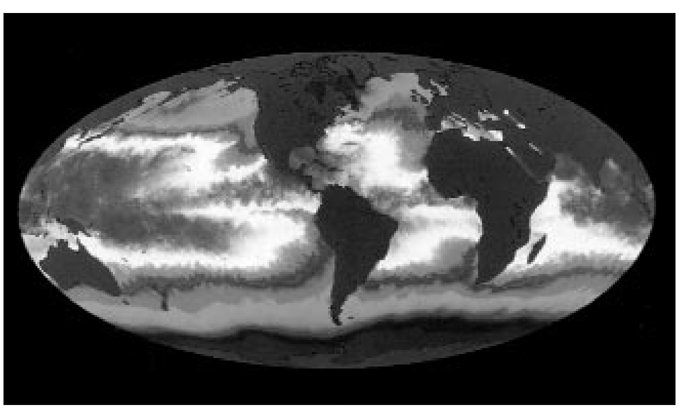

Fig 4-8

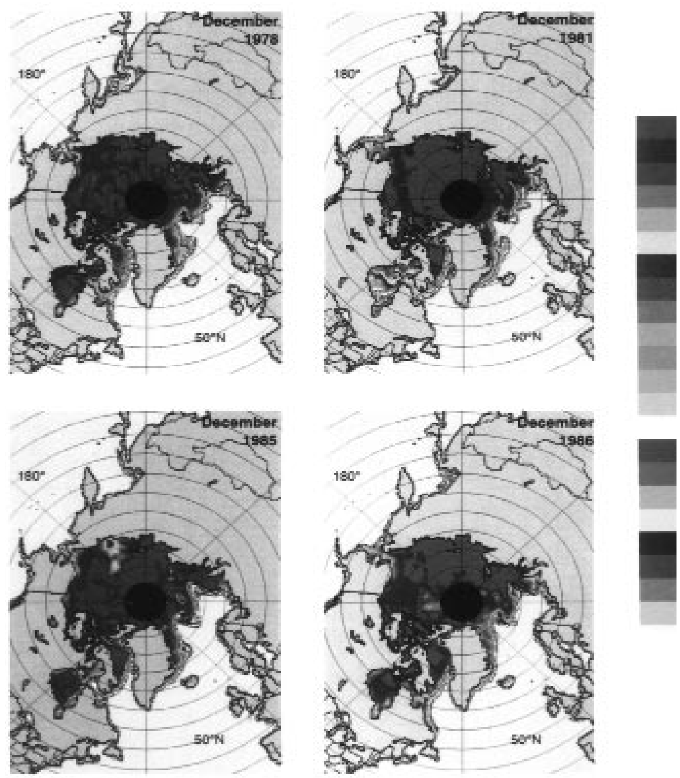

Fig 4-9

◆ **Earth Observing System (EOS):**

– *Atmosphere:* ACRIM will measure solar total irradiance; SOLSTICE will measure the total variation of UV and its contribution to the natural variability of ozone. MODIS, MISR and EOSP will detect regional and global changes in tropospheric aerosols. Stratospheric aerosols will be mapped and monitored by SAGE III. Volcanic gases can be measured with TES and MLS. AIRS/AMSU/MHS, MODIS, MISR, CERES and AMSR, together, provide measurements of water vapor, atmospheric temperature and cloud properties. HIRDLS will measure stratospheric cooling, a major expected signal of an increased greenhouse effect. TRMM will inaugurate development of the capability to measure precipitation more directly.

– *Ocean:* MODIS and AIRS/AMSU/MHS provide detailed measurements of sea surface temperature. EOS ALT produces a well-calibrated measurements of absolute sea level; surface winds will be obtained from scatterometer measurements. SEAWIFS and MODIS will monitor changes in the ocean biosphere through color changes.

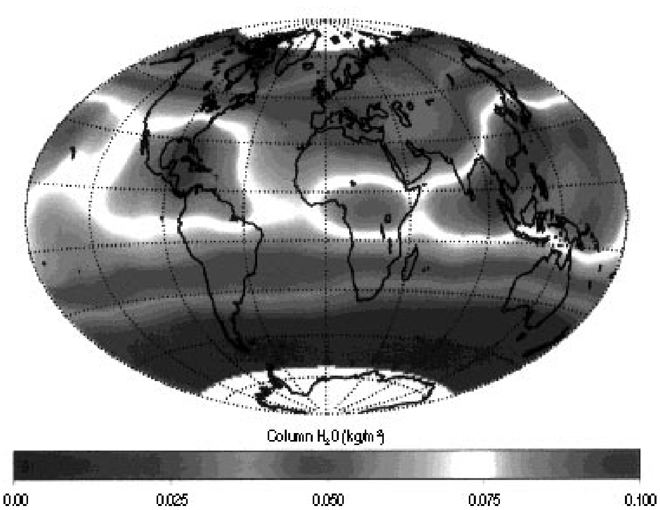

Fig 4-10

– *Land:* Landsat-7 will provide enhanced high-resolution observations of land surface properties. MODIS, ASTER and MISR will survey and characterize changes in land surface cover and surface vegetation. EOS analyses will also provide surface fluxes of energy and carbon.

– *Cryosphere:* GLAS will provide the first opportunity to obtain a global view of ice sheet mass balance.

– *Chemistry:* MOPITT and TES will measure CO and CH_4; TES will measure H_2O, O_3 and N_2O. EOS analyses will determine ozone depletion. MODIS measures of biomass burning will contribute to knowledge of trace gas emissions.

◆ **Earth System Science Pathfinders (ESSP) program:**

EOS observations will be augmented by a series of small spacecraft missions to implement key missing measurements, to target new questions that arise from ongoing studies, and to move towards completion of an Integrated Global Observing System.

3.2 Process Studies and Field Campaigns

◆ **Atmosphere:** Regional field experiments provide detailed information concerning climate relevant radiation exchange processes within the Earth's atmosphere. These experiments provide the reference data needed for quantitative interpretation of satellite data, as well as insight into the physical process studied. As described below, two series of regional field experiments have been sponsored by NASA to better understand the effects of atmospheric particulate matter, on the Earth's radiation balance.

– *Clouds and radiation:* Since the mid-1980's a series of regional field experiments have been conducted to better understand of the role of clouds on the Earth's radiation budget. The initial field experiment was called the First

ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE). Succeeding field studies continued with the same acronym. The FIRE III science team was selected in 1995 and has planned studies to understand the role of low level clouds in the heat budget of the arctic, and the impact of cirrus clouds on the radiation budget of the Earth, primarily at tropical and mid-latitudes. The Arctic component of the project is planned for 1998 in coordination with the Surface Heat Budget of the Arctic Ocean (SHEBA) regional experiment sponsored by NSF and ONR. The mid-latitude component is planned in 1996 to study cirrus development associated with aircraft contrails. The latter experiment is part of the interagency, Subsonic Aircraft Assessment (SASS) program.

– *Aerosols and radiation:* A Smoke, Clouds, and Radiation (SCAR-B) field experiment, the third in a series, was conducted in central Brazil in 1995. The overall goal of the SCAR experiments was to improve our understanding of the effects of anthropogenic aerosols on the Earth's radiation balance and climate. The observational approach adopted by the team of U.S. and Brazilian scientists was to obtain simultaneous *in situ* and remote sensing measurements of the physical and chemical properties of the aerosols produced by biomass burning and other human activities. SCAR-B *in situ* measurements also generated reference data for evaluation of remote sensing techniques, which will be used for the validation of the MODIS sensor on the EOS AM-1 mission.

◆ **Ocean:** Research on climate-related oceanic processes supported by MTPE support the research objectives of the WOCE and CLIVAR DEC-CEN international programs, i.e., the development and validation of coupled climate system models for climate change prediction and assessment of the representativity of available data sets for determining the state of the ocean circulation and long-term variations.

◆ **Land:** MTPE research on land surface processes related to the long-term climate issue is described in the MTPE Land-Cover/Land-Use Change section of this plan.

◆ **Cryosphere:** MTPE research on cryospheric processes support the scientific goals of WCRP/ACSYS, specifically understanding the interactions between the Arctic Ocean circulation, ice cover and the hydrological cycle, to provide a scientific basis for accurate representation of Arctic processes in global climate models. A similar effort is needed for the Antarctic.

◆ **Chemistry:** MTPE research focuses on understanding present stratospheric interactions with climate to aid in predicting the influences that future states of the stratosphere will have on the climate of the troposphere-stratosphere system. MTPE research addresses the issues of how natural and anthropogenic variations of the atmospheric composition may influence long-term climate. Emphasis is placed on climate changes resulting from alterations in the incoming and outgoing radiative fluxes. For example, changes in the distributions of radiative gases such as ozone would lead to changes in distributions of atmospheric temperature and wind and thus possibly affect the dynamical interactions between the stratosphere and troposphere, and ultimately the climate. Further information on MTPE research on atmospheric chemistry is included in the MTPE Atmospheric Ozone section of this plan.

◆ **Other relevant datasets (provided primarily by other agencies and programs):** All of these satellite data analyses can be supplemented by analyses of surface, aircraft, balloon and rocket datasets. Those that provide nearly-global information include:

– Surface and balloon weather observations provide information about clouds, in addition to characterizing temperature, humidity, winds, and precipitation. Assimilation in weather forecast models provides the best available information about the three-dimensional wind field. Networks of surface sites already or will soon provide measurements of ozone, surface radiation, and tropospheric aerosols.

– Ship and buoy measurements in the ocean of salinity, vertical temperature structure, biological production, and circulation continue to be the main sources of these quantities.

– Hydrological surveys and monitoring of river runoff must continue to supplement attempts to determine hydrological parameters from satellites.

– Snow depth and ice thickness information comes primarily from surface and aircraft measurements.

– Surface monitoring is the best source of atmospheric composition information for long-lived trace gases. Monitoring and study of urban pollution from surface and aircraft observations are key to understanding these processes.

3.3 Modeling Studies

MTPE EOS Interdisciplinary and R&A science investigators are engaged in the development of comprehensive climate system models and extensive model experimentation aimed at comparative assessments of potential human-induced and natural forcing changes.

◆ **Data Assimilation:** Space-based observations acquire added value when placed in the context of other data and the known mechanics of the coupled climate system. Data assimilation provides a dynamical, physical, and chemical framework for combining a large variety of satellite and *in situ* observations into globally consistent data sets suitable for climate research. Model-assimilated data set adds insight beyond what either the observations or the model alone can provide. Additionally, optimal observational requirements can be developed and model improvements can be accelerated and made more quantitative, because of the systematic confrontation between the model and the observations.

The NASA/GSFC Data Assimilation Office (DAO) is aiming to provide, from 1998 onward, a hierarchy of model-assimilated data sets for a variety of atmospheric, land-surface, and ocean-surface products. The DAO will provide near-real-time data sets for use by instrument teams and time-critical science applications. Delayed analyses (known as Platform Analyses) of MTPE satellite data, will use advanced assimilation techniques to address specific problems related to process representation. Long-term, internally consistent reanalyses will be developed specifically for climate applications, study of natural variability and model development. Prototypes of the complete hierarchy of analyzed data sets are currently available.

Development activities are focused on improving the data assimilation system. The DAO model is being expanded to accept new data types from NSCAT, TRMM, EOS-AM, EOS-PM and CHEM, as well as from advanced instruments on operational satellite systems. Simultaneously, work is proceeding to incorporate a broader range of physical processes in the model formulation, such as improved land-surface, cloud-water and cloud-ice parameterizations. The 1998 system will provide state-of-the-art use of moisture, rainfall, and hydrometeor observations and unique capabilities of land- and ocean-surface assimilation. Chemistry and transport models are also being adapted to serve in the data assimilation process. In total, the DAO activity is progressing in the direction of a coupled Earth-system model constrained by satellite observations. Sub-surface ocean and ecosystem data assimilation will be developed as separate activities at GSFC and other facilities before being combined with the DAO main stream.

Currently, there is no source for comprehensive model-assimilated analyses of the global ocean circulation (or transport of chemical constituents), due to the limited availability of deep ocean observation, the diversity of these observations (including Lagrangian tracer data) and the difficulty of validating any sub-surface analysis against a proper reference database. NASA is working with other research and science-funding agencies to address this generally-recognized need and develop a focused global ocean data assimilation facility capable of combining extensive satellite observations, especially surface wind and dynamic topography data from NSCAT and TOPEX-POSEIDON, with *in situ* hydrographic and tracer data assembled by the World Ocean Circulation Experiment (WOCE). As mentioned above, a longer-term goal is to combine atmospheric and oceanic data assimilation procedures in a coupled model driven data assimilation. (Refer to the MTPE Seasonal-Interannual Climate Prediction Program Plan for further information on NASA Data Assimilation efforts.)

◆ **Climate simulation and prediction:** The MTPE-supported modeling studies, model development and validation, and data assimilation research also contributes to resolving the scientific and methodological problems, identified by the USGCRP Forum on Global Change Modeling (October 1994), that limit the predictive capabilities of climate models. MTPE research contributions address the following issues:

– Process studies associated with cloud-radiation-water vapor interactions; ocean circulation and overturning, aerosol forcing; land surface processes including climate-induced changes in the functioning of ecological systems and global chemical cycles; improved representation of atmospheric chemical interactions within climate models leading to improved understanding of the causes of trends in CH_4, N_2O,O_3, CFCs, and aerosol effects on radiation transfer and cloud formation.
– Improved spatial resolution in atmospheric and ocean models.
– Improved model representation of the coupling between the atmosphere and oceans.
– More explicit model representation of land-surface processes including vegetation and soil characteristics.
– Global observations that are essential to force, initialize and diagnose model output.

To use global model output as a guidance tool for predictions of the natural system and for policy- planning purposes, it would be crucial to operate, in parallel, global observing systems to regularly update information on the state of the global system. This is particularly true of parameters specified as initial or boundary conditions in the models, as well as atmospheric constituents such as trace gases and aerosol three-dimensional distributions.

◆ **Impact studies:** Until fully-coupled Earth system models are available, some caution should be exercised in the interpretation and application of long-term predictions and assessments obtained from global models. Even “complete” global-system model predictions would contain inherent uncertainties and errors caused by the approximations used in handling non-linearities, the parameterization of physical processes, and the specification of initial and boundary conditions. Nevertheless, MTPE continues to support the improvement of global climate system models as valuable research and experimental tools to assess the impacts of climate changes induced by natural or anthropogenic factors.

3.4 New Technology

Understanding of long-term climate variability is particularly dependent on the availability of continuously calibrated, long-term measurements. Providing for accurate and reliable calibration of long-term satellite data records is a major technological challenge, that will continue to be the focus of MTPE's attention. The calibration of the multiple imaging radiometer systems is a scientific and technical focus of the EOS AM-1 mission. Further in the future, the MTPE's work on satellite instrument calibration technologies is expected to lead to the development of research-quality calibration methods and their implementation as standard practice, as part of an international Integrated Global Observing Strategy to provide consistent long term records of key Earth system variables. The New Millennium Program provides the opportunity for demonstration of key new space observation technologies for this purpose.

4. LINKS TO OTHER ORGANIZATIONS AND PROGRAMS

The NASA MTPE program achieves its full significance only as part of a wider inter-agency and international effort to understand the climate system. Key linkages include:

NATIONAL LINKAGES

◆ NOAA has primary responsibility for maintaining surface and space-based environmental observations of the global atmosphere and coastal waters. The continuation of these observations and their on-going improvement is the basis for NASA's planning in the field of climate studies. Both NOAA and NASA support a wide range of climate research studies. Moreover NASA brings its expertise in remote sensing and atmospheric radiation physics to bear through the cooperative Pathfinder program with NOAA.

◆ DOE, through its Atmospheric Radiation Measurement (ARM) program, is conducting detailed radiation and cloud studies from a series of densely instrumented surface sites that will be maintained for long-term monitoring. These sites also serve as anchors for conducting field campaigns as described above.

◆ NSF provides the majority of funding for basic disciplinary studies that are the foundation of climate and Earth system sciences. NSF supports major field observation projects, particularly for ocean process, atmospheric physics and polar studies (e.g., JGOFS, WOCE and SHEBA), and corresponding data analysis and research. In particular, NSF is the leading U.S. agency for research in both the Arctic and the Antarctica.

◆ DOD provides important complementary satellite observations of clouds, precipitation, sea ice, and air-sea fluxes from the DMSP operational satellite series and the GEOSAT follow-on radar altimetry satellite. The DOD/NOAA/NASA National Polar Orbiting Environmental Satellite System (NPOESS) will constitute the most effective means for sustained operational monitoring of a wide range of key climate parameters in the early 21st century.

◆ NRC's Climate Research Committee/Dec-Cen Panel provides guidance to NASA's Office of Mission to Planet Earth on scientific issues relating to long-term climate variability and change.

INTERNATIONAL LINKAGES

Two world-wide science coordination bodies organize international cooperative research programs on problems of climate and the biosphere: studies of the physical climate system are organized primarily by the World Climate Research Program (WCRP), while studies of the biosphere and its interaction with climate are organized primarily by the International Geosphere Biosphere Program (IGBP). Discipline-specific international coordination activities are similarly underway to organize cooperation for long-term monitoring of various sets of environmental parameters, including the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), the Global Terrestrial Observing System (GTOS) and the Global Atmosphere Watch (GAW).

The WCRP is organized into four major components which are meant to address key physical processes that are important for climate changes on different time scales. The fast climate processes, involving atmospheric clouds and radiation, precipitation and ground hydrology, are studied under the Global Energy and Water Experiment (GEWEX). Seasonal to century changes driven by atmosphere-ocean interactions and ocean circulation variability are studied under the Climate Variability program (CLIVAR) which address both seasonal-to-interannual time scales (CLIVAR/GOALS and longer time scales (CLIVAR/DEC-CEN). Research on longer-term changes builds upon the first global description of the deep ocean circulation, undertaken by the World Ocean Circulation Experiment (WOCE). The Arctic Climate System Study (ACSYS) addresses polar region climate problems. NASA's process studies fit well within this structure, whereas NASA's space-based measurements span all of these programs.

The IGBP is organized into six Core Projects, all of which are involved in the collection, management and interpretation of data and the development of predictive models. In addition, the IGBP Task Force on Global Analysis, Interpretation and Modeling (GAIM) focuses on synthesizing our understanding of global biogeochemical cycles and their linkages to the hydrologic cycle and physical-climate system.

In response to guidance from the White House Office of Science and Technology Policy (OSTP), NASA is working with other U.S. agencies on defining the concept, structure, of an Integrated Global Observing Strategy (IGOS), and the implementation strategy for the U.S. components of an internationally coordinated global observing system. The concept of an IGOS has arisen from a realization that the integration of existing and new potential observing capabilities into a coherent system would most efficiently serve the needs of society. To accomplish this goal, the IGOS will address three important tasks. The first is coordinating the recommendations of user groups, with different yet sometimes overlapping data requirements, to formulate the objectives of a multi-purpose observing and data systems. The second task is to ensure national commitments to the long-term implementation of the various components of a coherent global system. The third is the coordination of operating agencies plans, including both space-based and *in situ* observing systems and their associated data systems, to minimize duplication and enhance the complementary nature of each component. These three tasks constitute the purpose of IGOS.

In addition, important contributions to decadal-to-centennial climate research are currently being realized through bilateral agreements with several foreign space agencies, including the TRMM and ADEOS satellite programs led by Japan, the ERS-1 and -2 multi-purpose Earth observation satellite program of ESA, the TOPEX/POSEIDON ocean altimetry satellite mission implemented jointly with CNES, and the RADARSAT program of Canada.

5. FUTURE PLANS AND ACCOMPLISHMENTS

5.1 MILESTONES

As suggested by the NASA MTPE Strategic Plan, it is appropriate to have a gradually shifted emphasis from Characterization-to-Understanding-to-Prediction and Assessment. However, all three activities must occur simultaneously, indeed all three are necessary to evaluate progress.

CHARACTERIZATION (at all scales):
(* indicates an Approved Program or Project; † indicates an operating or past program)

- Present: continued measurements from TOPEX/POSEIDON†, ERS-1† and 2†, DMSP SSM/I† for ocean circulation, sea ice, and air-sea exchange, continued extension of ISCCP cloud properties to include particle size and liquid and ice water paths, continued characterization of profiles of stratospheric ozone, water vapor and aerosols from SAGE† and UARS†.

- ◆ 1996: NASA Scatterometer (NSCAT[†]) will map winds at the ocean surface globally.
- ◆ 1996: SAR maps of Antarctica will map surface snow and ice topography.
- ◆ 1997: Experimental precipitation measurement test incorporating the first space flight of a precipitation radar (TRMM*) along with new series of Earth radiation budget measurements (CERES*) will provide first simultaneous space measurements of latent heating and radiation.
- ◆ 1998: First flight of SAGE III* (Meteor) will continue the measurements of stratospheric aerosols and trace gases.
- ◆ 1998: Airborne laser survey of Greenland will provide the first continental-scale indication of the ice sheet mass balance.
- ◆ 1998: Flight of AM-1* including new CO measurement (MOPITT*), improved tropospheric aerosol and cloud measurements (MODIS*, MISR*) and enhanced land surface measurements (ASTER*).
- ◆ 1999: First flight of long-term solar monitoring mission to extend the ACRIM* data record.
- ◆ 1999: Flight of ADEOS II* with SEAWINDS to measure ocean surface winds.
- ◆ 1999: First flight of EOS* radar altimeter to monitor ocean circulation.
- ◆ 2000: First small satellite (Smallsat) flight making high-precision measurements of tropospheric aerosols and cloud microphysics.
- ◆ 2000: Flight of PM-1* including enhanced temperature and humidity measurements, may serve as prototype for future NPOESS sensors.
- ◆ 2001: TRMM follow-on mission to extend tropical measurements of convective rainfall.
- ◆ 2001: First flight of EOS ALT* laser to monitor sea level and ice sheet topography.
- ◆ 2002: Flight of CHEM-1* to measure key tropospheric chemical constituents.
- ◆ 2003: Fully implement NASA component of long-term climate measurement systems (solar irradiance, ozone, aerosols, cloud microphysics).

UNDERSTANDING (climate process scales):

- ◆ 1996: Complete ABLE III* field campaign to improve our knowledge of tropospheric chemistry.
- ◆ 1997: Initiate tropical latent heating (precipitation) and cloud- radiation process studies (TRMM*).
- ◆ 1998: Complete SHEBA/FIRE (Arctic)* field phase to provide measurements of radiation properties of the polar atmosphere and surface.
- ◆ 1998: Initiate advanced aerosol and hydrological process studies (EOS-AM1*).
- ◆ 2000: Complete LBA/FIRE* (tropics) field phase to characterize energy exchange in the tropical rain forest.
- ◆ 2000: Initiate advanced water vapor, cloud, and sea ice process studies (EOS-PM1*).

PREDICTION AND ASSESSMENT
(global and regional scales):

During 1996–2002, contribute toward developing comprehensive and capable Earth System models, improving the realism of coupled atmospheric-ocean-land surface models and expanding their capability by coupling the core model with other components of the Earth System. Test these different coupled models by means of comparisons with observations, especially with the detailed data available for the period 1979–2002. Model development, testing and applications will be carried out in collaboration with the academic research community (e.g., through AMIP). The overall Earth system model development program will require continuing coordination with NOAA, NSF, and DOE. Key milestones in model development and testing are:

- 1997: Test and compare several coupled atmosphere-ocean models, using their ability to simulate climatology and observed climate changes over the period 1979–1996 as evaluation criteria. Begin efforts to quantify the utility of satellite data in an ocean data assimilation scheme and in coupled atmosphere-ocean prediction systems.

- 1999: Complete and test individual coupling of models for several processes with the core model. Specific models will include: dynamic sea ice, stratospheric chemistry, and ecosystem models.

- 2002: Complete and test coupling of core multi-component model with ocean chemistry model for carbon cycle and ocean tracers, tropospheric chemistry, and ice sheet dynamics.

Modeling activities anticipated in the period 1996–2002 would also include continued improvement of atmospheric and oceanic model physics, focusing on radiation, convection, cloud cover and optical properties, the boundary layer, ocean sub-grid scale mixing parameterizations, deep ocean convective processes, and land surface processes. The coupled models will be used to contribute to assessment activities, including IPCC climate assessments, WMO/UNEP ozone assessments, and NASA subsonic and supersonic aircraft assessments. An additional activity will be to continue interactions with climate impact assessment modelers, with the key milestones:

- 1997: Assess the ability to simulate climate impacts via the combination of climate simulations with off-line ecosystem and agricultural impact models, focusing on the period 1979–1997, for which satellite data on the natural ecosystem and agricultural data will be available.

- 1999: Compare, improve, and make consistent the land surface parameterizations in GCMs (e.g., PILPS) and impact models.

- 2001: Include water resources as an explicit variable in long-term economic model(s), and evaluate the possibility of including temperature effects more directly in these integrated assessment models.

- During the period 2003–2009 the coupled models will play a central role in improving our understanding of Earth System changes. This will result from an integration of the results of process studies which should provide improved representation of key components of the climate system within the global-scale models. In this period it should be feasible to couple several different sub-models. The models can be compared not only with a 30-year record of global observations from space, but also it should be feasible to run the models for the century time scale, and thus to compare the pre-industrial and current situations.

- During the period 2010–2016 the models should be sufficiently developed and tested via comparisons with observations that they can be used for limited reliable forecasts and assessments of the Earth System. The models should be relevant to practical applications, the previous development and testing having been focused on regional climate and on coupling with models designed for climate change impact assessment.

5.2 Expected Accomplishments

Although it is clearly understood that predicting the future outcome of scientific research has risk, we believe that sustained progress in implementing the broad program outlined in this plan, in similar plans promulgated by the other Federal Agencies, and by the international scientific community, should lead to accomplishments such as the following in documenting the state of the Earth's climate, understanding the key processes which dictate its response to natural and human induced forcings, and demonstrating skill in predicting long-term changes:

CHARACTERIZATION (all scales):

- 2000: Multi-decadal record of primary global climate forcings (e.g., solar irradiance, atmospheric composition, clouds, aerosols).
- 2000: Multi-decadal record of primary radiative feedbacks on climate, including their variations during a series of climate events, such as El Niño and volcanic eruptions.
- 2010: Multi-decadal record of key climate responses: troposphere/stratosphere temperature and humidity profiles, ocean temperature and salinity profiles, land surface temperature, sea ice and snow cover, radiation budget at top of the atmosphere and surface, precipitation, and ice sheet volume.

UNDERSTANDING (process scale):

- 2005: Improved global model treatments of atmospheric radiative transfer, atmospheric chemistry, cloud physics, aerosol processes, precipitation, air-sea exchanges, sea ice, ground hydrology , and ocean circulation.
- 2005: Improved assessment of global sea level change and its causes.
- 2010: Complete first set of global models coupling troposphere, stratosphere, ocean, land, cryosphere, chemistry and biosphere.
- 2010: Improved determination of climate sensitivity and analysis of the role of anthropogenic forcings in observed climate variations and trends.

PREDICTION AND ASSESSMENT
(global and regional scales):

- 2010: Ability to make limited realistic predictions of regional climate changes and their impacts that will occur in response to long-term climate forcings.
- Continuing: Major contributions to national and international scientific assessments of climate change, such as IPCC, that will provide the scientific basis for environmental policy formulation.

Major contributions to this section were provided by: James Hansen, William Rossow, Pierre Morel and Robert Schiffer. For more information concerning NASA's research program on long-term climate variability and change, contact: Dr. Robert A. Schiffer at: (202) 358-1876 or via internet at: rschiffer@hq.nasa.gov

Section 5

Atmospheric Ozone Research

EXECUTIVE SUMMARY

NASA maintains an extensive research program related to atmospheric ozone in order to provide high quality scientific data on both the troposphere and stratosphere to the scientific community and to policy-makers who use such information in setting environmental policy. NASA takes a distinctly global viewpoint in this research, making observations over all parts of the Earth and heavily utilizing global models. NASA research in this area has been a major contributor to the overall effort involving other U.S. Government agencies, scientists from academia, industry, and government, as well as foreign entities. These efforts address the science agendas developed through peer-led groups, notably the International Global Atmospheric Chemistry (IGAC) Program of the International Geosphere-Biosphere Programme (IGBP) and the Stratospheric Processes and their Role in Climate (SPARC) group of the World Climate Research Programme (WCRP). NASA managers, researchers, and grantees have played significant roles in internationally-sponsored assessments, such as the World Meteorological Organization/United Nations Environment Programme, *Scientific Assessment of Ozone Depletion* and the *Climate Change* assessments of the Intergovernmental Panel on Climate Change.

Underlying NASA's ozone research is the knowledge that concentrations of ozone and related atmospheric constituents have changed in the past and are likely to change in the future. Changes are due to both natural and human activities, and a particular emphasis of NASA's work is the quantitative determination of present distributions and past variations. Anthropogenic changes can result from use of chlorofluorocarbons (CFCs) and related halogen-containing hydrocarbons, commercial and military aviation, and increased production of chemically and radiatively active gases such as methane and nitrous oxide. The key questions concerning atmospheric ozone facing the scientific community are thus:

- What is the global distribution of ozone in the troposphere and stratosphere and how has it changed in the recent past?

- Are the processes responsible for transport, production, and loss of trace constituents in and from the troposphere and stratosphere sufficiently well understood that predictive models for the chemical state of these regions can be developed?

- Are the current international agreements limiting the production of ozone-destroying chemicals having the expected effect on the atmospheric concentration of these species, and on ozone levels?

- What are the effects of aviation (both the current subsonic fleet and the projected subsonic and supersonic fleets), the fumigant methyl bromide, and industrially produced CFC-replacements, on the distribution of ozone and other trace constituents in the atmosphere?

- How will changing climate due to increased concentration of radiatively active trace gases affect future distributions of ozone and other chemically reactive species, such as photochemical oxidants?

In order to help answer these questions, NASA's atmospheric ozone research plan includes several types of research:

- To characterize the global distribution of ozone, chemically active trace constituents, aerosols, and related meteorological parameters (e.g., temperature), including long-term observations of a subset of these parameters;

- To understand the processes responsible for the chemical transformations of trace constituents, the role of aerosols in affecting atmospheric chemistry, and the transport of trace constituents within the stratosphere, between different atmospheric levels (stratosphere/troposphere, stratosphere/mesosphere), and between the troposphere and the Earth's surface; and

- To quantitatively model the trace constituent composition of the troposphere/stratosphere system through the combined application of observations and global models.

The NASA research plan addresses these objectives through several program elements:

- **Laboratory Studies of Fundamental Processes,** including thermodynamic, photochemical, and spectroscopic properties of atmospheric trace constituents, covering both gas- and condensed-phase species (the latter including aerosol particles).

- **Process Studies and Field Campaigns,** involving focused measurements within a particular atmospheric region so that specific chemical and physical processes can be understood and theories can be quantitatively tested; these rely extensively on *in situ* and remote-sensing aircraft measurements, as well as those from ground-, balloon-, and space-based instruments.

- **Long-term Global Measurements,** including space-based measurements of ozone and other parameters, as well as ground-based measurements of concentrations of species whose concentrations are affected by ozone distributions.

- **Modeling Studies,** emphasizing global models that can be used both for retrospective data analysis and for predictive studies of the future atmosphere.

Developments which have the potential to significantly enhance NASA's abilities to investigate atmospheric chemistry and which will be incorporated into the NASA program as they become available include.

- **The launch of the Earth Observing System** beginning in 1998, especially in regards to the determination of global distributions of tropospheric ozone and its precursors for an extended period of time.

- **The availability of remotely-piloted aircraft,** which will allow for higher altitude *in situ* and remote sensing measurements than currently available from manned aircraft, as well as longer flight duration and more flexible flight trajectories.

- **The availability of massively parallel and other high performance computing systems,** which will facilitate development and operation of more complex atmospheric chemistry models, especially three-dimensional chemistry/transport models emphasizing the troposphere and the combined effects of long-term chemical and climatic changes associated with increasing trace gas concentrations.

The development of Earth System Science means that NASA's atmospheric ozone research will also become more closely linked to the other science themes of Mission to Planet Earth (especially the long-term climate change theme) than in the past.

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ATMOSPHERIC OZONE RESEARCH

I. Introduction

NASA's research goals related to atmospheric ozone are to develop a detailed understanding of chemical, physical, and radiative processes affecting distributions of ozone and oxidizing species in the global troposphere and stratosphere, to accurately and precisely determine those distributions, including their spatial and temporal dependence, and to quantitatively characterize observed past and, through the use of predictive models, potential future changes in these distributions in response to specified forcings.

These goals arise from three separate, but related scientific issues—each of which has broad policy implications. First, the absorption of biologically damaging ultraviolet (UV) radiation, especially in the 290–320 nm region, by ozone plays an important protective role in the Earth environment. Reductions in atmospheric ozone amounts would lead to increased flux of ultraviolet radiation at the surface, assuming other factors, such as cloudiness, remain unchanged. This would have harmful effects on plant and animal life, including human health. Second, ozone absorbs and emits radiation in several wavelength ranges, and is an important contributor to the physical state of the atmosphere and thus to the Earth's climate. Finally, ozone, together with the hydroxyl radical (OH) which is formed photochemically from ozone and water vapor, serves as a major oxidizing species in the atmosphere. Changes in ozone amounts, especially in the troposphere, will affect the lifetime of many atmospheric trace species, including both chemically active species (e.g., chlorofluorocarbon replacements) and radiatively active species (e.g., methane) and could thus have an indirect effect on their contributions to ozone depletion and climate change.

NASA's efforts are carried out in response to and in the context of federal legislation; indeed, the NASA Authorization Act and the U.S. Clean Air Act require NASA to carry out research on stratospheric ozone and to report to Congress on a triennial basis. As scientific knowledge has evolved, recognition of the coupling between tropospheric and stratospheric chemistry has become clearer. Both must be understood if existing measurements of ozone and its future evolution are to be understood.

A particular emphasis of NASA's activities is the characterization of both natural and human-induced variations on atmospheric ozone amounts, as one cannot be understood without knowledge of the other. There have been important changes in ozone distributions, including the "Antarctic Ozone Hole" in which a significant fraction of the ozone over Antarctica is lost in the spring (especially in the lower stratosphere), much smaller reductions in ozone amounts over most of the Earth's surface (again, mainly in the lower stratosphere), and increases in ozone amounts in the upper troposphere in many, but not all, locations.

Among the human-induced variations are the effects of changing concentrations of halogen-containing species in the atmosphere. These compounds, which have been implicated in the above-noted ozone depletion, are currently subject to both domestic and international regulations (the Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments and adjustments). Stratospheric chlorine levels are expected to peak at about the turn of the century and remain greater than those of today for at least a decade, meaning that (all other atmospheric parameters being equal) stratospheric ozone amounts will reach their minima during that time. Major elements of NASA's ozone efforts in the next decade are, therefore, to characterize and understand ozone distributions during this most sensitive time period. Additional elements are to assure that atmospheric halogen levels are responding as expected to legislation and to relate the observed ozone distribution to that expected based on the observed halogen distribution and other forcing factors (e.g., solar radiation) to test whether the atmosphere is behaving as expected. Underlying NASA's work is the recognition that ozone changes can only be understood in the context of a broad range of measurements of atmospheric parameters (other trace constituents, aerosols, dynamical information).

One issue of particular interest to NASA is the role of aviation in affecting the ozone distribution in the upper troposphere and lower stratosphere. This is true for both current subsonic and projected supersonic aircraft. Since major decisions about future aircraft (in particular, engine technology) will be based in part on environmental considerations, it is critical that these decisions are supported by sound scientific data and methodology.

At the surface, ozone constitutes an important pollutant, which is harmful to plant and animal life. Although urban air quality is not a NASA responsibility, NASA is concerned that the interface between air quality and global change be properly addressed, and therefore expects to pay increased attention to this coupling in the future (see section IV.B). In this document, unless otherwise specified, the term troposphere is used to refer to the free troposphere.

In carrying out its research on atmospheric ozone, NASA fully participates in interagency and international programs and projects. It has a strong commitment to participation in, and in many cases, leadership of internationally sponsored assessments and peer-organized programs. International cooperation in space-based measurements has been significant, and will increase in importance in the future.

II. Background

In this section, accomplishments of NASA's ozone and atmospheric chemistry research programs, the current structure of those programs within NASA, and the science questions which are being addressed now and for the foreseeable future are summarized.

A. Recent Accomplishments

Over the past decade and a half, NASA's research program, together with those of its domestic and foreign partners, has made significant progress in characterizing the distribution of ozone and other trace constituents in the atmosphere, identifying the processes which control them, and developing a suite of models which can be used both to test our understanding of the atmosphere and for predictive purposes. Particular highlights include the following:

- Demonstration that chlorine is directly involved in depletion of lower stratospheric ozone during Antarctic spring ("Ozone hole" conditions);
- Recognition that the same chemical processes occur in the Arctic and Antarctic lower stratosphere during spring, and that the lack thus far of an "ozone hole" in the Arctic is due to differences in dynamics between the two hemispheres;
- Demonstration of the key role which chemical reactions occurring on the surface of aerosol and polar stratospheric cloud particles play in controlling the chemical composition of the lower stratosphere;
- Demonstration of significant isolation between wintertime polar vortices and mid-latitudes, as well as significant downward transport in these vortices over the course of the winter;
- Characterization of long-term changes in stratospheric ozone distributions, including evidence for statistically significant depletion of ozone over most of the Earth's surface, with largest changes occurring in the lower stratosphere during winter and spring;
- Determination of the global distribution of many trace constituents, including most important nitrogen-containing species and halogen reservoir species, leading

to clear demonstration that most of the stratospheric halogen is of anthropogenic origin;

- Determination of long-term growth in anthropogenically-produced halogenated source gases at the Earth's surface over most of the 1980s, followed by leveling off of growth and, for some species, slow decline in the mid-1990s in response to limitations on production as required by the Montreal Protocol;

- Demonstration of consistency between burdens and changes in concentrations of halogenated source gases in the troposphere and those of halogen-containing reservoir species in the stratosphere over the course of a decade;

- Characterization of the role which major volcanic eruptions, notably El Chichon (1982) and Mt. Pinatubo (1991), play on the chemistry and dynamics of the stratosphere;

- Development of two-dimensional assessment models which are used for both retrospective data analysis and for future assessment, including calculation of atmospheric effects of projected CFC replacement molecules;

- Development of improved understanding of the effects of present and projected aviation activities on atmospheric composition, including the first ever *in situ* sampling of an aircraft plume in the stratosphere;

- Demonstration of the adequacy of current theories relating relative concentrations of photochemically active trace constituents with laboratory measurements of the rates of the underlying photochemical processes;

- Characterization of global distributions of tropospheric ozone and carbon monoxide using direct and/or inferred measurements, with particular recognition of spatial and temporal variability associated with biomass burning in Africa and Latin America;

- Characterization of the effect of outflow from Asian continent on the global troposphere, including determination of seasonal variation; and

- Characterization of the effects of chemistry in plumes from biomass burning on distributions of ozone and other trace constituents in Atlantic free troposphere.

B. Organization of NASA's Ozone Research Effort

Scientific Research

Ozone research within the Science Division of the OMTPE is concentrated in three research programs as well as in the Earth Observing System (EOS) Interdisciplinary Science Program, and science teams and guest investigator programs for ongoing space missions. These are:

- The Upper Atmosphere Research Program (UARP), which conducts laboratory measurements, and ground-, balloon-, and aircraft-based measurements related to the stratosphere. Some process modeling is done under UARP as well.

- The Tropospheric Chemistry Program (TCP), which emphasizes airborne field studies of the remote troposphere. As for UARP, process scale modeling is done under TCP.

- The Atmospheric Chemistry Modeling and Analysis Program (ACMAP), which emphasizes global scale chemical models of the troposphere and stratosphere, as well as the model-based analysis of trace constituent data for the troposphere and stratosphere. Studies of stratospheric dynamics are also part of ACMAP, as are large-scale modeling studies which attempt to relate atmospheric composition to processes occurring at the Earth's surface. Reprocessing and reanalysis of "old" global data sets is also carried out by ACMAP. Modeling activities supported by ACMAP play an important role in the planning, execution, and analysis phases of field experiments conducted under UARP and TCP.

- The Earth Observing System (EOS) Interdisciplinary Science (IDS) program supports two IDS efforts focusing on stratospheric chemistry. Several additional tasks focusing on the combined modeling for atmospheric chemistry and climate were selected in response to the recent augmentation of the EOS IDS program (see section VI.A).

- The Guest Investigator Program (GIP) for NASA's Upper Atmosphere Research Satellite (UARS) and the Science Team for the Second Stratospheric Aerosol and Gas Experiment (SAGE II) instrument

Mission Operations and Data Analysis (MO&DA)

The MO&DA activities are carried under the supervision of the Mission to Planet Earth (MTPE) Program Office at NASA's Goddard Space Flight Center (GSFC). MO&DA supports data analysis, algorithm development, archiving, and early-stage science validation for NASA-operating space assets, including the Total Ozone Mapping Spectrometer (TOMS), the Solar Backscatter Ultraviolet (SBUV/2), the Stratospheric Aerosol and Gas Experiment (SAGE II), the Upper Atmosphere Research Satellite (UARS), and Shuttle Solar Backscatter Ultraviolet (SSBUV) instruments. As new NASA-funded instruments begin operating, MO&DA assumes responsibility for their operation.

Flight Systems

The MTPE Program Office at GSFC also supports the development of flight hardware, including pre-launch science and algorithm costs. Major systems here include the TOMS instruments, with three instruments scheduled for launch before the turn of the century (Earth Probe TOMS, launched in July 1996, ADEOS TOMS in August 1996; and Meteor-3M TOMS in 2000). It has begun funding of the Shuttle Ozone Limb Sounder Experiment (SOLSE) which is intended for flight on the Space Shuttle in 1997 assuming an appropriate manifest opportunity exists.

Costs for developing EOS instruments and their associated algorithms and science definition efforts are provided through the MTPE Program Office. This includes the three U.S. (or jointly U.S. and foreign) provided instruments on the EOS CHEM mission (launch scheduled in 2002): the Troposphere Emission Spectrometer (TES), the High Resolution Dynamics Limb Sounder (HIRDLS), and the Microwave Limb Sounder (MLS). FSD will also support the U.S. team to be selected for the Japanese-provided Ozone Dynamics Ultraviolet Spectrometer (ODUS) on the EOS-CHEM platform. The Stratospheric Aerosol and Gas Experiment (SAGE III) instruments scheduled for flight in 1998 on a Russian Meteor-3M spacecraft and for the Space Station in ~2001 are also supported by the MTPE Program Office.

Future flight opportunities for atmospheric chemistry instruments may become available under the Earth System Science Pathfinder (ESSP) program and the New Millennium Program (NMP). The latter is a joint activity sponsored by MTPE and the Office of Space Access and Technology.

Atmospheric Effects of Aviation Project (AEAP)

This project is funded by the office of Aeronautics, but is implemented in close collaboration with MTPE. AEAP efforts are responsive to two separate aeronautical programs—the High Speed Research Program (HSRP) focusing on the development of a "next generation" supersonic transport aircraft which would be economically viable and environmentally benign, and the Advanced Subsonic Technology Program (ASTP) which is attempting to improve various operational aspects of the current commercial subsonic fleet. The atmospheric components of HSRP and ASTP are contained within AEAP and have been designated as the Atmospheric Effects of Stratospheric Aircraft (AESA) and Subsonic Assessment (SASS) projects. The goal of AEAP is to focus and, when necessary, redirect atmospheric science investigations towards the particular atmospheric perturbations resulting from aircraft exhaust. Thus AEAP augments and in some areas extends ongoing activities in the core MTPE science programs related to tropospheric and stratospheric ozone. AEAP-supported tasks include laboratory studies, field measurements, process-scale modeling, and global modeling. In addition to its focus on ozone, AEAP supports research on aerosols, clouds, and radiation, it also includes topics which are more specific to the aircraft engine environment, such as characterizing emitted species and studying changes to the exhaust gases and particles in the plumes and wakes of aircraft.

C. Current Science Questions

Many of the science questions to be addressed in the coming few years have been included in the previous section, but it is helpful to summarize them before moving onto longer term plans, including new directions and emphases, which are expected.

These questions may be broken up into two classes: broader questions about what has happened and/or will happen, and more specific questions about what must be understood in order to develop the knowledge base needed to answer the first class of questions. Typically, the former class of questions will involve the construction of extended data sets and/or computational models, while the second set will involve the detailed understanding of relevant processes.

Key current science questions include but are not limited to the following:

1. Stratospheric Ozone:

a. Broad Questions

– Can we understand the tropical and mid-latitude changes in total ozone and in its vertical distribution over the last 15 years, including the quantitative assignment of the origin of these changes to chemical and dynamical processes and arctic ozone depletion?

– Can we quantitatively explain the interannual variability in the strength, size, and persistence, of the Antarctic ozone hole?

– Can we demonstrate that both surface and stratospheric concentrations of halogen-containing species are behaving as expected in response to international agreements restricting their use, as well as known sources and loss properties of the species?

– Can we accurately simulate how the atmosphere responds to large volcanic eruptions, including both past (e.g., the El Chichon and Mt. Pinatubo eruptions) and any future eruptions?

– Can we accurately predict perturbations to ozone distributions which would be caused by future aircraft operations, especially supersonic civil transport aircraft, as well as potential future industrial chemicals?

– Can we accurately predict how the thermal and dynamical properties, and through them the chemical properties, of the stratosphere will change in response to increasing concentrations of radiatively active gases?

b. Process Questions

– Can we quantify transport of trace constituents across atmospheric barriers, including the tropical/mid-lati-

tude barrier, the mid-latitude/polar vortex barrier, and also across the tropopause?

– Can we refine our knowledge of the roles which halogen-containing species play in the stratosphere, including reactions which repartition chlorine and bromine among their various compounds, and the reactions of iodine-containing species in the lower stratosphere?

– Can we improve our understanding of the formation and characteristics of particles in polar stratospheric clouds and aerosols throughout the stratosphere?

– Can we understand the relative importance of the various cycles for ozone production and loss throughout the stratosphere, particularly at altitudes where the chemistry transitions from heterogeneous to homogeneous control?

2. Tropospheric Ozone:

a. Broad Questions

– Can we characterize and understand the record of changes in ozone profiles in the free troposphere, including spatial and temporal variability?

– Can we quantitatively determine the atmospheric lifetimes of hydrogen-containing species such as methane and HCFCs and understand how these may change as the trace constituent composition and dynamical properties (e.g., temperature, moisture) of the atmosphere change?

– Can we determine what role, if any, subsonic aircraft operations have had on tropospheric trace constituent distributions, and what effect future operations of increased numbers of aircraft might have?

– Can we predict what changes in surface production of chemically active trace constituents such as nitrogen oxides, methane, carbon monoxide, and non-methane hydrocarbons will have on the composition of the global troposphere?

– Can we better determine the distribution of tropospheric ozone through application of current space-based remote sensing techniques, as well as those projected for the future?

– Can we estimate the net processing effect of clouds on the trace constituent distribution of the upper troposphere?

– Can we quantify the impact of stratospheric changes (e.g., ozone depletion) on tropospheric chemistry, especially that due to increased penetration of ultraviolet radiation?

– Can we improve our understanding of the budgets of biogenic organic and inorganic trace species that play major roles on tropospheric ozone, including isoprene, CO, CH_4, and methyl halides?

b. Process Questions

– Can we quantitatively understand the contributions of different sources to ozone distributions in the remote troposphere, including the relative contributions of outflow from developed regions, biomass burning, *in situ* production, and downward transport from the stratosphere?

– Can we quantify the sources of total reactive nitrogen in the upper troposphere, including the spatial and temporal dependence of contributions from *in situ* emission by aircraft, *in situ* production by lightning, downward transport from the stratosphere, and upward transport of species emitted at the surface?

– Can we improve our knowledge of the relative distributions of reactive nitrogen compounds in the troposphere through improved measurements and models so that current discrepancies between observations and model calculations can be resolved?

– Can we determine what role chemical processes occurring on dust and aerosol particles, as well as in clouds, and wet/dry deposition at the surface, play on the trace constituent composition of the global troposphere?

– Can we determine what role, if any, halogen species play in the chemistry of the global lower troposphere?

– Can we accurately characterize the processes by which naturally and anthropogenically produced sulfur-containing species are oxidized in the atmosphere to sulfuric acid and thus contribute to aerosol formation and/or growth?

III. Elements of NASA's Ozone Program

NASA's ozone research can be divided into six categories, with close interaction between each of them. NASA strives to maintain a balanced program among these areas, including consideration of both short- and long-term horizons, and strives to maintain sufficient flexibility that it can deal with new scientific issues as they arise. The following section briefly describes the work in each of these areas. Present and future measurement capabilities for different atmospheric trace constituents are summarized in Appendix 5-1.

A. Laboratory Science

Laboratory measurements of fundamental physical and chemical problems may be thought of as coming in three separate areas. First, laboratory measurements of rates of chemical kinetic and photochemical processes, are carried out to support understanding of atmospheric transformations and for inclusion in computational models, including detailed process models and global atmospheric chemical models. In recent years, much of this activity has centered on chemistry and spectroscopy of halogen-containing molecules, including oxides and other compounds, of chlorine, bromine, and most recently, iodine. Processes which lead to ozone production in the troposphere have also been studied. Results of laboratory measurements are critically evaluated in the *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling* report, which is published biennially and represents the community consensus of reaction rates, cross sections, and quantum yields. The laboratory techniques may be applied to help determine the atmospheric lifetimes of potential future industrial chemicals which may impact the ozone layer or atmospheric radiative forcing.

Second, spectroscopic measurements (and some related photochemical phenomena) are made to support NASA's remote sensing efforts, including those for ground-, balloon-, aircraft-, and space-based platforms. Particular areas of emphasis include spectroscopy of polyatomic molecules at the temperature and pressure conditions appropriate to the stratosphere and upper troposphere, which will be needed to fully utilize observations made by the EOS HIRDLS, TES, MLS, and SAGE III instruments, and photochemical and spectroscopic parameters needed for the interpretation of lidar measurements made both from the ground and from aircraft.

Finally, thermodynamic properties and associated kinetic information on atmospheric aerosol and stratospheric cloud particles are studied. Attention has been focused on the three-component system water-nitric acid-sulfuric acid under stratospheric conditions. Continued emphasis on this area is called for, as there are outstanding questions about the identity of particles present in polar stratospheric clouds and lower stratospheric/upper tropospheric aerosols, as well as the detailed mechanism by which they form. There is also appreciable work remaining on the physical and chemical properties of stratospheric sulfate aerosol particles and ternary liquid droplets. Longer-term efforts are needed to characterize the properties and impacts of soot particles in the atmosphere and optical properties of aerosols, in order to evaluate the feasibility of using infrared remote sensing techniques for the determination of aerosol composition and density.

B. Ground-Based Measurements

NASA's ground-based measurements center on the use of globally-distributed high-quality research instruments for the determination of long-term changes in atmospheric trace constituent variability. The two major efforts in this area are the AGAGE (Advanced Global Atmospheric Gases Experiment, formerly the ALE-GAGE - Atmospheric Lifetime Experiment—Global Atmospheric Gases Experiment) and the Network for the Detection of Stratospheric Change (NDSC). These programs provide critical monitoring of the surface concentrations of both anthropogenically and biogenically produced trace gases (AGAGE) and of the chemical composition of the lower stratosphere (NDSC).

AGAGE uses gas chromatography and gas chromatography coupled with mass spectrometry to measure with high frequency the concentration of naturally and anthropogenically-produced atmospheric gases at the Earth's surface. AGAGE stations are shown in Figure 5-1. The emphasis in AGAGE is on halogen-containing species (although nitrous oxide and methane are measured), with its original focus on chlorinated species having been expanded to bromine-containing species like halons and methyl bromide, as well as HCFCs (see Appendix 5-1). AGAGE investigators have a significant modeling program to ensure that their full global data set is exploited.

Ground-Based Detection Sites

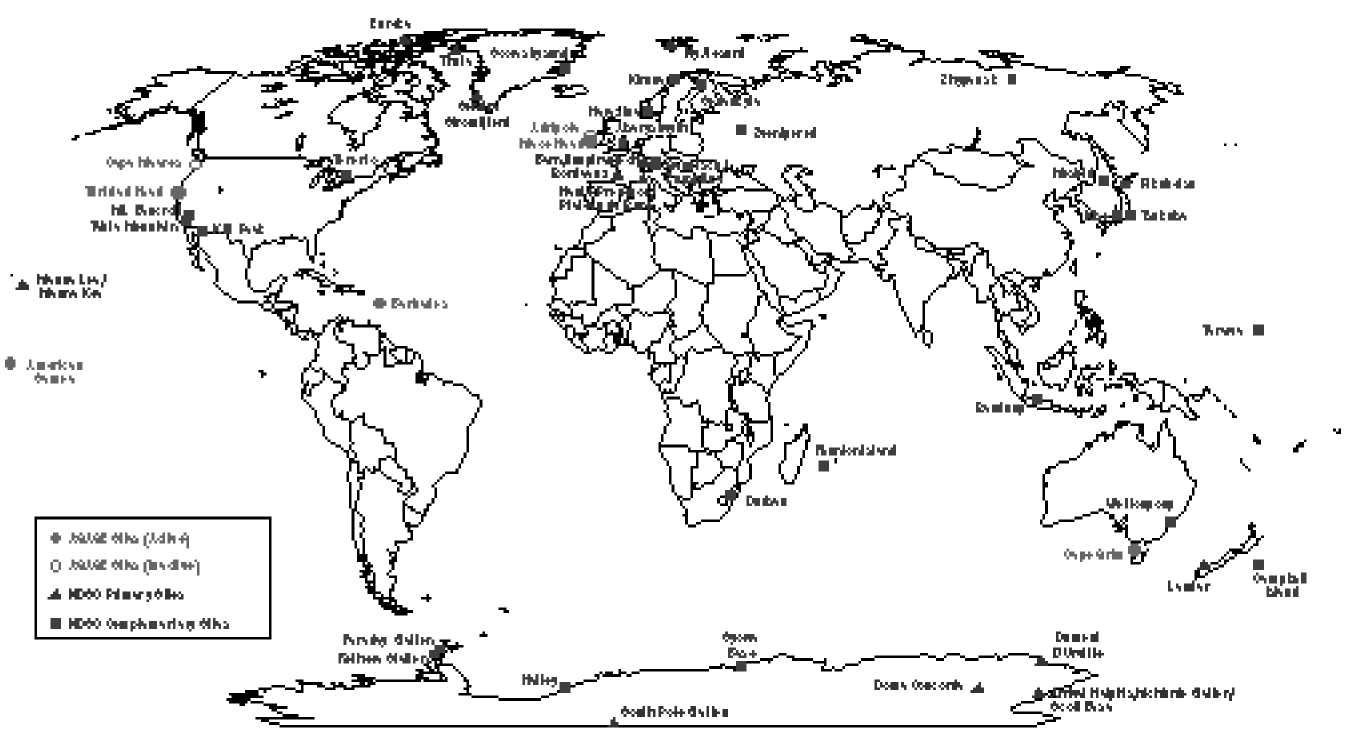


Fig5-1

NDSC is an internationally directed and sponsored program (major support from NASA, NOAA, and foreign partners) in which a number of remote-sensing instruments meeting mutually-agreed upon standards are deployed at sites around the world. Major instrument categories deployed at the NDSC's "primary sites" include Fourier transform interferometers, millimeter wave emission spectrometers, visible/UV absorption spectrometers, and lidars; together these provide measurements of column amounts and/or profiles of atmospherically important species. In addition to the primary NDSC sites, complementary sites involving a less complete set of instruments are also participating. Primary NDSC sites and a summary of complementary sites are also given in Figure 5-1. Since consistency of calibration, both across instruments and over long time periods, is a hallmark of the NDSC program, there will be a continuing program of instrument comparisons through laboratory and field efforts. NDSC has a program for associated modeling investigations to help ensure that data will be fully utilized. NDSC instruments have also been involved in validation measurements for space-based instruments, and provide measurements in support of aircraft campaigns.

C. Balloon-Based Measurements

NASA has a long heritage of using balloons to measure the trace constituent composition of the middle atmosphere. There are three major applications of the balloon program. First, balloons provide a unique way of covering a broad range of altitudes for *in situ* (or remote sensing) measurements in the stratosphere. Of particular interest is the 22–40 km region which is above the altitude range of current airborne platforms such as the ER-2. In some cases, a combination of instruments on a single balloon gondola can provide a complete measurements set which can be utilized together with process models to carry out detailed tests of photochemical theory. A balloon component, known as Observation of the Middle Stratosphere (OMS), is planned in association with the transport-focused STRAT series of ER-2 missions (see below).

Second, balloon instruments provide the opportunity for correlative data for space-based measurements, including both validation ("atmospheric truth") and complementary data (for example, measurement of species not measured from the space-based instrument). Balloon instruments formed a critical part of the correlative measurements program for the Upper Atmosphere Research Satellite (UARS), and current plans are to use some of NASA's balloon instruments in support of the validation program of the Japanese ADEOS satellite (launch scheduled August 1996) and the European ENVISAT (launch scheduled in 1999).

Finally, balloon-based platforms constitute important venues for testing instruments under development. These can be either potential instruments for uncrewed aerial vehicles (UAV) or, in some cases, for space-based remote sensing instruments.

D. Aircraft-Based Measurements

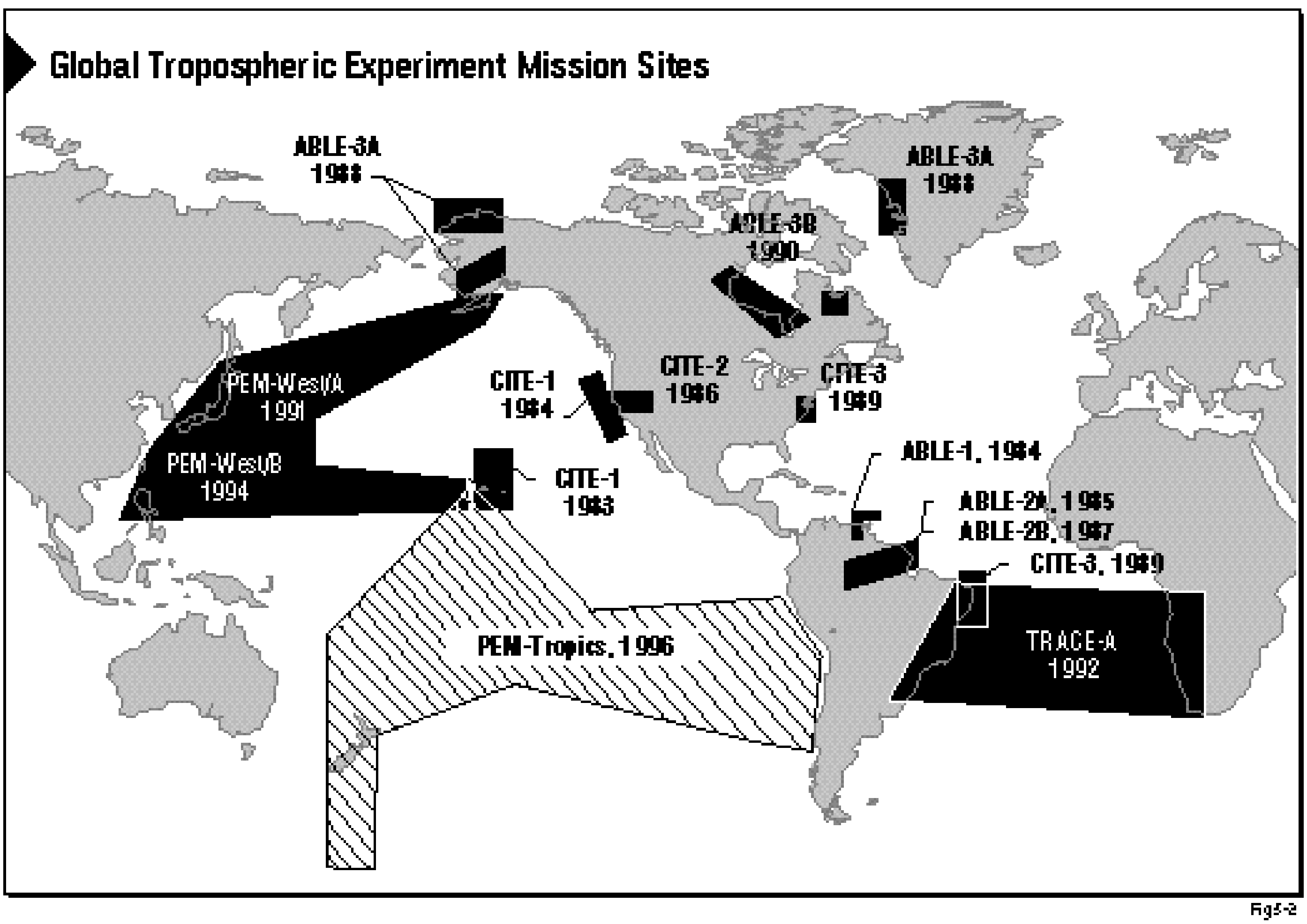
Aircraft-based measurements for tropospheric ozone have recently centered on use of the NASA DC-8 aircraft for measurements of ozone, other trace constituents, and meteorological parameters in the remote troposphere. This aircraft includes both *in situ* instruments and an ozone/aerosol lidar for remote sensing (both above and below the aircraft). A map showing the geographical distribution of tropospheric chemistry aircraft missions is given in Figure 5-2. The focus of these missions has been the remote troposphere in order to define the tropospheric background and to look at effects of human activities

Fig. 5-1 (left): Map showing geographic locations of AGAGE ground measurement sites and NDSC primary and complementary sites. Note that Trinidad Head AGAGE station does not begin operating until 1996, while period of operation for Irish stations was 1978–1983 for Adrigole and since 1987 for MACE Head. The Cape Meares station operated only from 1980 to 1989.

which influence the troposphere on a regional-to-global scale. Such activities include biomass burning from South America and Africa and the large continental outflow of pollution from North America and Asia. The next major tropospheric aircraft campaign will be in the central Pacific Ocean area in July–September, 1996 (Pacific Exploratory Mission—Tropics, or PEM-Tropics). This mission will include both the DC-8 and P-3 aircraft. This will be followed by the Global Tropospheric Experiment/ Transport and Atmospheric Chemistry Experiment (GTE/TRACE B) mission to Brazil in February-April, 1999. This will be done as part of a coordinated NASA-field study in Brazil addressing surface-oriented climate, ecology, and biogeochemistry. The subsequent GTE aircraft mission, whose exact nature has not yet been determined, is tentatively scheduled for 2001. In the time between PEM-Tropics and GTE/TRACE-B, there will likely be an aircraft instrument intercomparison, focusing on OH and NO_x measurements.

Stratospheric aircraft campaigns involve both the ER-2 and DC-8. Over the past decade, campaigns emphasized

Fig. 5-2 (below): Map showing geographic distribution, chronology, and names of Global Tropospheric Experiment (GTE) aircraft missions carried out as part of NASA's tropospheric ozone research activities.



high latitudes in both the northern and southern hemisphere (Airborne Antarctic Ozone Experiment—AAOE in 1987, first Airborne Arctic Stratospheric Expedition - AASE I in 1988–89; second Airborne Arctic Stratospheric Expedition—AASE II—in 1991–1992; and the recently-completed Airborne Southern Hemisphere Ozone Experiment/ Measurements for Assessing the Effects of Stratospheric Aircraft—ASHOE/MAESA). The more recent campaigns have also focused on the midlatitudes (Stratospheric Photochemistry, Aerosol, and Dynamics Expedition—SPADE campaign) and the tropics (ASHOE/MAESA). The aircraft campaigns support both the basic science objectives and UARP and the more applied needs of AEAP. During ASHOE/MAESA, for instance, the ER-2 was able to sample the plume of a Concorde flying near New Zealand.

The current ER-2 payload provides *in situ* measurements of nearly all important trace constituents in the lower stratosphere, including the important radical species OH, HO_2, NO, NO_2, ClO, and BrO. Together with measurements of source and reservoir gases, this payload provides for critical tests of photochemical models in the lower stratosphere (see Appendix 5-1). A representation of the latitudinal coverage of past, present, and future stratospheric aircraft missions is given in Figure 5-3.

Most recent aircraft campaigns include the recently initiated Stratospheric Tracers of Atmospheric Transport (STRAT) campaign, a 3-year (1995–1997)multi-deployment ER-2 campaign focusing on transport of long-lived trace gases in the lower stratosphere, and The Vortex Ozone Transport Experiment/Tropical Ozone Transport Experiment (VOTE/TOTE) mission, which used the DC-8, equipped for both remote sensing and *in situ* observations, to focus on transport across the winter polar vortex/midlatitude and the subtropical barrier,

Fig. 5-3 (below): Schematic diagram showing latitudinal distribution and chronology of stratospheric aircraft missions along with representation of significant processes affecting stratospheric ozone distributions.

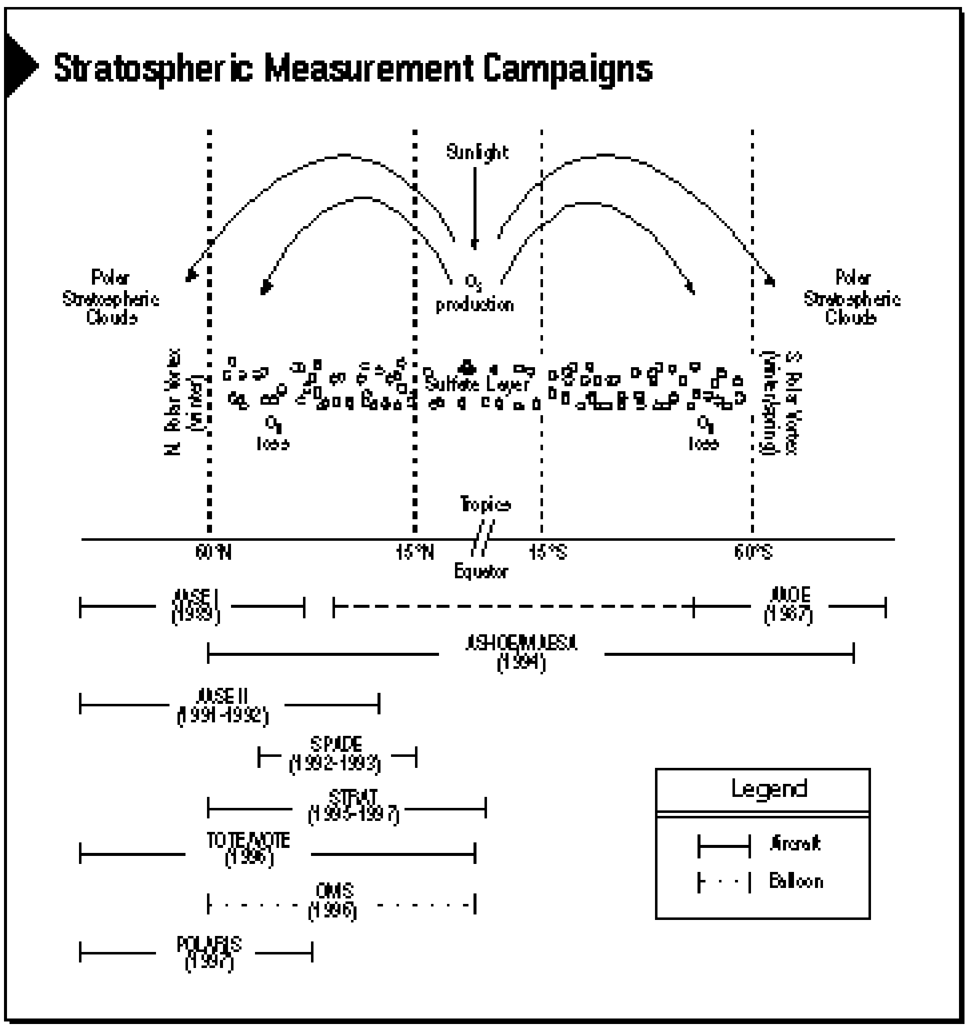


Fig5-3

respectively. In particular, VOTE/TOTE inaugurated the use of a newly-developed methane/water vapor/temperature lidar system, which complemented the existing ozone/aerosol lidar by providing simultaneous information on dynamically controlled constituents. During operations of these missions, there was an opportunity for the ER-2 to sample the DC-8 plume.

A focused ER-2 chemistry experiment, known as Photochemistry of Ozone Loss in the Arctic Region in Summer (POLARIS) is planned for the spring and summer of 1997 to provide the first summer-time measurements in the northern mid-high latitude stratosphere. This mission, to be based in Alaska, Hawaii and California will consist of three three-week deployments, and will emphasize detailed chemistry observations. A balloon campaign (see section III.C) may be implemented as part of POLARIS.

A new chlorine nitrate *in situ* instrument is expected to be ready for the late 1996 ER-2 deployment as part of the STRAT campaigns. This continues the improvement of ER-2 instruments. New ER-2 instruments introduced in the past few years include a lidar for remote sensing measurements of tropospheric water vapor, aerosols, and clouds, as well as *in situ* instruments for measuring H_2O_2, OH, HO_2, CO_2, UV radiation, CFCs and numerous other halogen and hydrogen-containing species, and N_2O, SF_6, CH_4, CO, HCl, and NO_2. New DC-8 instruments include improved lidar instruments, including those for tropospheric and stratospheric ozone and aerosols, clouds, and tropospheric water vapor, and fast response *in situ* measurement for trace gases such as O_3, CH_4, and CO.

The Subsonic Assessment Program of the Atmospheric Effects of Aviation Project will be sponsoring dedicated use of airborne platforms to support its objectives. A DC-8 based campaign SASS Ozone and Nitrogen Oxide Experiment (SONEX) to investigate the sources and chemistry of upper tropospheric and lower stratospheric NO_x ($NO_x = NO + NO_2$) and its role in ozone formation is planned for the summer of 1997. The SONEX campaign will include measurements both inside and outside the heavily trafficked North Atlantic flight corridor to try to help asses the contribution of emissions from currently-operating subsonic aircraft to the budgets of ozone and NO_x in these regions. SASS is also planning to initiate support for development of a single integrated instrument package designed for simple and economical use aboard commercial aircraft. This package would help generate a spatially and temporally extensive measurement set for key tracers of atmospheric transport in the troposphere and lower stratosphere, and would likely include one or more tracers with surface sources and simple atmospheric chemistry, one with seasonally-varying sources and/or more complex atmospheric chemistry, a stratospheric tracer, and water vapor. Proposals in both these areas have recently been requested under a NASA Research Announcement issued for AEAP/SASS (NRA-96-OA-01).

In 1998 and beyond, there will quite likely be a series of aircraft flights as part of the validation program for EOS instruments (see following section). The first atmospheric chemistry instruments to be launched include the Measurement of Pollution in the Troposphere (MOPITT) and the Stratospheric Aerosol and Gas Experiment (SAGE III) instruments. Aircraft campaigns using an airborne version of MOPITT, as well as *in situ* sampling instruments for both CO and CH_4, are planned. Since SAGE III makes measurements in both the troposphere and stratosphere, aircraft campaigns involving aircraft capable of flying in both regions of the atmosphere are planned. The solar occultations for the SAGE III instrument all take place at high latitudes, and the aircraft validation campaigns in support of SAGE III will probably emphasize the high latitude northern hemisphere.

The atmospheric aircraft campaigns, especially the stratospherically-oriented ones, are closely tied in with MTPE's modeling and satellite programs. Modeling groups play a significant role in the aircraft campaigns. Most missions have "theory teams" designated as part of the overall science teams, and individuals associated with them participate intimately in the planning, operation, and data analysis of the missions. Satellite data are involved in several ways. Data from NASA's TOMS instrument have been most extensively used in order to help with flight planning in both the tropospheric and stratospheric campaigns, and global meteorological data (including assimilated data) are also used in this way.

In the longer-term, UAVs are expected to play a significant role in the atmospheric chemistry programs. UAVs are likely to have the capability to fly higher in the stratosphere than the ER-2, and may also be able to fly longer (both in terms of time and distance) which would facilitate types of flight paths not possible with current aircraft. MTPE has recently agreed to support an effort to prepare a payload for a UAV (Perseus B) which would measure the radiation field in the tropopause region together with the concentration of several radiatively active trace species (notably O_3 and H_2O). Instrument development for UAVs has also begun (see section IV.B.1).

E. Space-Based Measurements

The best known parts of NASA's space-based measurement program for ozone are the long-term ones which have been useful in characterizing the global aspects of ozone distribution and of long-term changes over more than 15 years. There are three such instrument sets: the Total Ozone Mapping Spectrometer (TOMS), the Solar Backscatter Ultraviolet (SBUV) series (done in conjunction with NOAA), and the Stratospheric Aerosol and Gas Experiment (SAGE) series. NASA (and, in the case of SBUV/2, NOAA) will continue operation of these instruments throughout the decade with a minimum (or, if launch schedules and instrument lifetimes permit, an absence) of data gaps. Operation of these instruments will be accompanied by continuing calibration, validation, and data analysis efforts in order to ensure that these critical instruments are returning data which is useful for trend studies (typically, precision of 1 percent/decade, which imposes constraints on absolute accuracy and long-term stability of instruments). As part of the calibration and validation process, periodic reprocessing of data sets is likely, and NASA will need to maintain sufficient capabilities so that these can be accomplished. The next generation SAGE instrument which will have a lunar occultation mode as well as the solar occultation mode of SAGE II, along with increased spectral resolution, number of channels, and instrument sensitivity and dynamic range. Earth Probe TOMS was launched on July 2, 1996, and future launch dates are August 1996 for ADEOS TOMS, and 2000 for Meteor-3M TOMS, approximately 1998, 2000, and 2003 for SBUV/2, and 1998 and approximately 2001 for SAGE III.

The Upper Atmosphere Research Satellite (UARS) will continue to be operated as long as the spacecraft and instruments so warrant. The spacecraft has already exceeded its design life, and plans are now focused on continuing measurements for a long time period. This will likely involve restricting operation of some instruments which have already begun to have problems or are thought to be less critical for extended operation, especially now that UARS is forced to operate in a "reduced power" mode. In particular, operation of the HALOE instrument, which provides measurements of profiles of ozone and other important gases, notably the halogen reservoir species hydrogen chloride (HCl) and hydrogen fluoride (HF), use of the MLS instrument for measurement of stratospheric ClO, HNO_3, and O_3, as well as upper tropospheric H_2O, and the solar measuring instruments (Solar Ultraviolet Spectral Irradiance Monitor and Solar Stellar Intercomparison Instrument for spectrally-resolved UV radiation and the Active Cavity Radiometer Irradiance Monitor for total solar irradiance), will continue for as long as possible.

NASA is making limited use of the Space Shuttle for atmospheric chemistry measurements. The Shuttle Solar Backscatter Ultraviolet (SSBUV) instrument made its last planned flight STS-72, launched January 11, 1996. NASA is sponsoring the German Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere—Shuttle Pallet Satellite (CRISTA-SPAS) payload for a shuttle flight in summer, 1997. The CRISTA-SPAS, together with its companion instrument, the Middle Atmosphere High Resolution Spectrographic Investigation (MAHRSI) instrument, provide unique data in several areas, including small-scale dynamical variability in trace constituent composition (CRISTA), and measurements of hydroxyl in the upper and middle stratosphere (although the ability of MAHRSI to measure OH in the middle stratosphere has yet to be quantitatively demonstrated). The Shuttle Ozone Limb Sounder Experiment (SOLSE) is currently under development at the Goddard Space Flight Center; this would function as a "proof-of-concept" for an ultraviolet limb sounder, which is a potential "next-generation" ozone profiling instrument. A flight opportunity for SOLSE (preferably the same flight as CRISTA/MAHRSI) has been requested.

Tropospheric carbon monoxide measurements will be made with some vertical profile information (4 levels) from the MOPITT instrument scheduled for launch aboard the first EOS spacecraft (EOS AM) in 1998. Additional space-based measurements of CO will be made from the MicroMAPS instrument on the Clark spacecraft, scheduled for launch in late 1996, and the "MAPS on MIR" mission, which is scheduled for launch in January 1997. The former will measure CO distributions at three pressure levels in the troposphere over the latitude range from 82 degrees north to south for a period of at least one year, while the latter will make measurements over the latitude range from 53° north to south for a 3–6 month period. The MOPITT instrument will also measure total column methane.

The chemistry (CHEM) platform of the Earth Observing System, to be launched in 2002, will have four complementary instruments which utilize different wavelength regions and viewing techniques to measure ozone and related atmospheric constituents. Three will focus on the stratosphere—the High Resolution Dynamics Limb Sounder (HIRDLS), an infrared emission spectrometer which will also measure small-scale dynamical variability in trace constituent distributions, the Microwave Limb Sounder (MLS), which will measure concentrations of many radical and reservoir species, and the Japanese-provided Ozone Dynamics Ultraviolet Spectrometer (ODUS), a "next-generation" TOMS-like instrument which will provide daily maps of total ozone. The remaining instrument, the Tropospheric Emission Spectrometer (TES), will measure profiles of ozone and several other important constituents in the troposphere, and will also measure a number of species in the lower stratosphere. HIRDLS and MLS are designed to provide information on the upper troposphere as well as the stratosphere. There have been numerous discussions about possible changes to the CHEM mission, including modifications to one or more instruments, and the exact payload arrangements and schedule for this mission are subject to change.

The SAGE III instrument is slated for flight aboard a Russian Meteor-3M spacecraft in 1998 and the International Space Station in approximately 2001. These are in complementary orbits—the polar sun-synchronous orbit of Meteor-3M will put the SAGE solar occultations at high latitudes, while the inclined orbit (51.5°) of Space-Station will provide solar occultation coverage from the tropics to approximately 65° latitude. Lunar occultations will cover a broad range of latitudes, and will provide the opportunity for measurements of NO_3 and OClO, which are only present in significant amounts at nighttime due to their rapid photolysis during the day.

Additional instrument concepts are being considered by NASA investigators for possible space flight, and may be proposed in response to the Earth System science Pathfinder announcement released in the summer of 1996.

In addition to its emphasis on present and future spacecraft, NASA also supports analysis, interpretation, and in several cases, reprocessing of historic space-based data sets. These efforts are focused to allow for more direct comparisons of older measurements with newer ones, in spite of differences in instrument or technique. Several examples of these efforts are underway, including reprocessing of Limb Infrared Monitor of the Stratosphere (LIMS) data from Nimbus 7 (data from 10/78–5/79) to provide optimal comparisons with data from infrared instruments on UARS, and reanalysis of BUV data from Nimbus 4 (early 1970s) and Selective Chopper Radiometer data (mid-1970s) for comparison with TOMS data, especially over Antarctica. Studies are also being carried out to extend profiles of trace constituents measured by the Atmospheric Trace Molecule Spectroscopy (ATMOS) instrument during its four Shuttle flights into the middle and upper troposphere, as well as to further refine its measurements of concentration profiles of some 30 stratospheric species.

NASA is also beginning a closer cooperation with NOAA concerning the possible development of ozone-measuring instruments for the NPOESS in which DOD, NOAA, and NASA have been directed to combine their operational measurements into a single suite. The major need in this area is to find a replacement for the SBUV/2 instrument, which suffers from numerous limitations, including low vertical resolution and an inability to measure the ozone profile below the peak in the ozone layer. The replacement instrument (or instruments) should have capability for both total ozone and ozone vertical profile measurements, with improved vertical resolution and measurement capability in the lower stratosphere.

F. Modeling and Data Analysis

Models play an important role in NASA's atmospheric chemistry efforts. Models are used both to provide a means to test our understanding of processes affecting the distribution of ozone and other trace constituents and of the past evolution of these distributions, as well as for forecasting the future evolution of the atmosphere based on prescribed scenarios. Global models are a particular focus of these efforts both because of the global nature of the atmosphere and the processes controlling its trace constituent distribution, and because of the significant amount of global data NASA produces through its measurement programs. Development and evaluation of these models requires the availability of fundamental data on atmospheric processes (see section III.A) as well as atmospheric measurements (sections III.B–III.E).

NASA's modeling and data analysis efforts have been closely tied to the assessment effort, notably the WMO/UNEP ozone assessments and also the IPCC climate assessment. The NASA modeling community also participates in the AEAP assessments of atmospheric effects of aviation (1995 supersonic aircraft assessment underway, preliminary subsonic aircraft assessment planned for 1996). Model intercomparisons (including both model-model and model-data) are typically done in conjunction with the assessment efforts. A summary of past, present, and potential future model intercomparisons and assessment applications is given in Figure 5-4.

The smallest-scale type of modeling carried out typically attempts to explain multiple observations in a narrow range of time and/or space. Photochemical box models and parcel trajectory models form the backbone of these process modeling activities. There is a strong synergy between laboratory science, field observations, and process-scale modeling. Process models can also lead to improved parameterizations which can be put into global models.

Global data sets are interpreted in light of calculations made with two- and three-dimensional global chemistry/transport models and statistically-oriented data analysis. The spatial and temporal dependence of ozone related to forcing factors such as the 11-year solar cycle, the quasi-biennial oscillation, and long-term change in atmospheric trace constituent composition are best examined with multi-dimensional models.

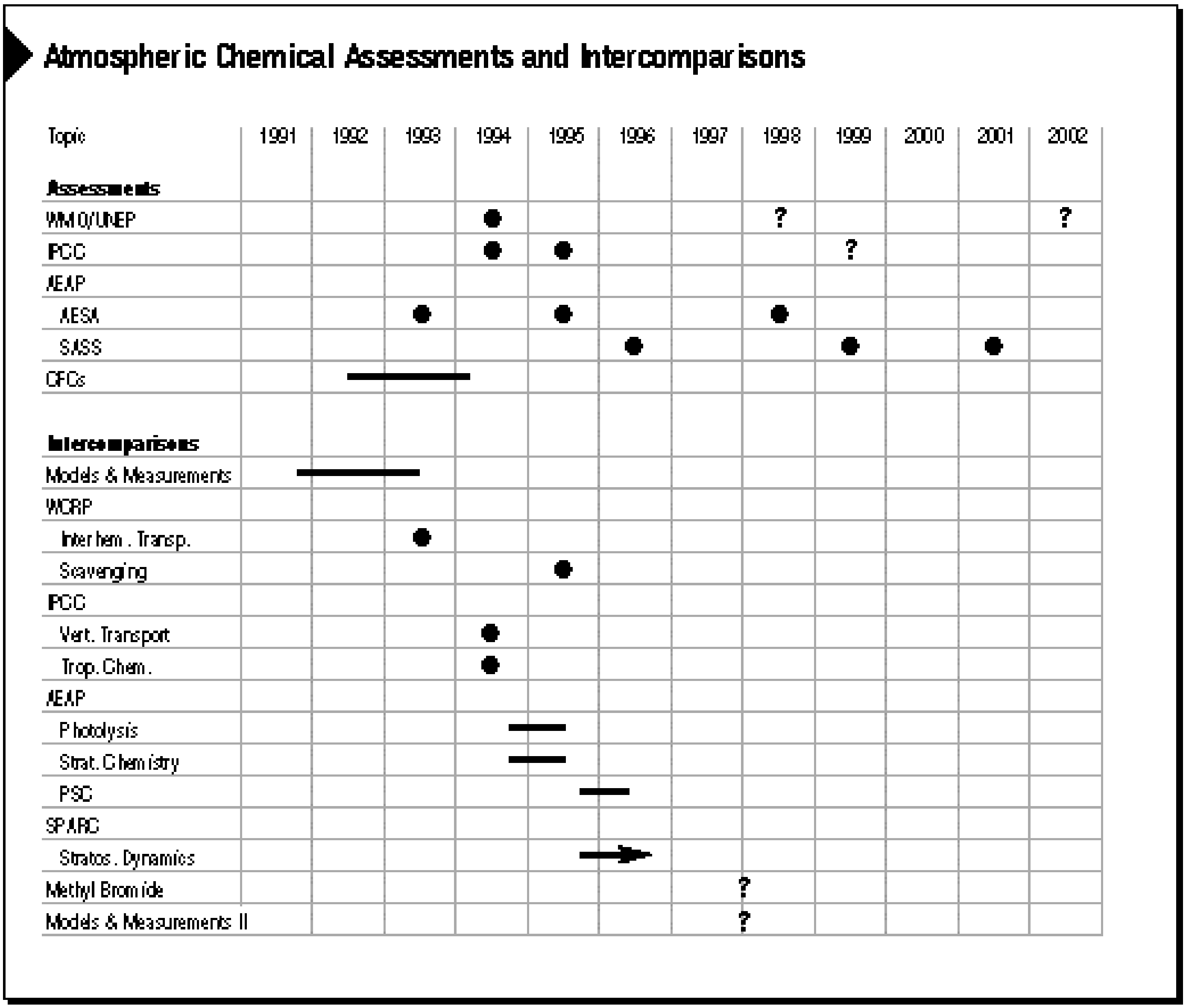


Fig 5-4

Fig. 5-4 (above): Timeline showing assessments and intercomparisons for atmospheric chemistry.

Fig. 5-5 (opposite): Schematic diagram showing hierarchy of atmospheric chemistry models, broken down by class (box, parcel trajectory, 1-D, 2-D, 3-D) showing options for different aspects of models.

NASA supports some regional scale modeling efforts, especially in tropospheric chemistry. NASA-sponsored work in this area typically focuses on those regions where the tropospheric chemistry aircraft missions have been flown, such as the East Asian area of the two PEM missions flown to date (PEM WEST A, PEM WEST B), and the South America-Africa regions sampled by the Transport and Atmospheric

Chemistry Near the Equator—Atlantic (TRACE-A). Some regional models also emphasize issues such as convective transport of trace gases and cross-tropopause transport associated with tropopause folds.

The major part of NASA's modeling effort is in global two- and three-dimensional atmospheric chemical models. A hierarchy of atmospheric chemical models is given in Figure 5-5. Two-dimensional (2-D) models have formed the backbone of the assessment modeling effort for the stratosphere. Particular interest lies in the development of "interactive" 2-D models which attempt to simulate the combined dynamical, radiative, and chemical response of the atmosphere to changes. Such models, although suffering from limitations inherent in 2-D models, may be especially useful in contributing to long-term assessments where agents of climate change (e.g., increased carbon dioxide) will lead to changed atmospheric temperature fields and resulting dynamical ones.

The importance of three-dimensional (3-D) models will increase in the future. This is particularly true for tropospheric chemistry, where there is strong longitudinal and temporal variability in species such as the oxides of nitrogen and ozone. Aviation-related issues, including those for both subsonic and supersonic aircraft, also indicate the use of 3-D models. Three-dimensional chemistry/transport models will use wind fields from general circulation models and data assimilation systems. While most of the 3-D chemical models have been run "off-line" wherein the chemical constituent distributions do not affect the dynamics, it is likely that in the next few years, chemistry-transport studies will be done "on-line."

A major lesson of the last decade has been the important roles of aerosol and cloud particles in controlling the trace constituent distribution of the stratosphere, and model development in the future will emphasize appropriate treatment of particles and their interaction with chemistry (and, where needed, radiation). In particular, aerosol/cloud microphysical models will likely need to be incorporated into 3-D models, which will place further strain on computational resources. The presence and effects of aerosols, clouds, and dust particles in global tropospheric models must also be considered for future inclusion.

Schematic Heirarchy of Atmospheric Chemistry Models

Class of Model	
0-D	Photochemical Box Model
1-D	Steady-state: some constituents prescribed from measurements Time evolving
2-D	Choices of dynamics: Fixed K_{yy}, etc. / K_{yy} from data / Interactive Dynamics / wave-breaking parameterizations Evolution of chemistry: Gas phase only; chemistry now includes reactions on aerosols, PSCs
Parcel Trajectory	Basic trajectory / Contour advection / Reverse domain filling
3-D	Low resolution 3-D models (e.g., 3 wave models) *Off-line models* (stratosphere typically before troposphere) – Choice of winds: - mechanistic models - GCMs - strat. analysis (forced at bottom) - data assimilation *On-line models* – interactive radiation/dynamics (prescribed chem., e.g., O_3 hole) – fully interactive models

Fig 5-5

IV. Links to Other NASA Activities

A. Other Research Foci Within MTPE

NASA's efforts in atmospheric ozone and chemistry have some overlap with the other research foci currently underway within MTPE. Several of these relationships have been mentioned in the text, so these are briefly summarized here:

1. Seasonal-to-Interannual Climate Variability

Much of NASA's efforts in stratospheric chemistry are to understand the evolution of ozone over the recent past (during which there have been good global or near-global observations of total ozone using space- and/or ground-based measurements). This ties in with NASA's interests in studies of seasonal-to-interannual variability in climate. Changes in atmospheric ozone can only be understood in the context of changes in temperature, and processes which affect the thermal structure of the surface-atmosphere system, such as the El Niño Southern Oscillation and the Quasi-Biennial Oscillation. These have been shown to have a measurable effect on the distribution of atmospheric ozone. Volcanic eruptions similarly perturb both the chemical and dynamical state of the atmosphere. The stratosphere may provide a significant downward forcing on the troposphere, especially as it is forced by the 11-year solar cycle through the absorption of short wavelength ultraviolet light by ozone. Finally, data assimilation procedures, which have been used almost exclusively for meteorological parameters, are now beginning to be used for chemical constituents (see section VI.B).

2. Long-Term Climate Variability:

The development of research and assessment models which can simulate the long-term changes in concentrations of ozone, aerosols, and other radiatively active species in the atmosphere is an important part of NASA's atmospheric chemistry research program. These models must correctly account for changes in climate due to changing trace gas concentrations and/or land-use patterns. In turn, distributions of radiatively active species are needed as input for climate models. Ultimately, a suite of coupled models, which account for changes in both chemical and thermal properties of the atmosphere, must be developed. In the interim, models which do not fully represent the range of couplings are used.

3. Land-Cover Change:

Tropospheric concentrations of biologically-produced trace gases, such as methane, carbon monoxide, nitrous oxide, and methyl bromide, will depend on the rates by which they are emitted by vegetation, industry, and other human activities at the Earth's surface. Changes in land use patterns can therefore affect trace constituent distributions in the atmosphere. This input is needed, both for understanding past trends in trace gases, and in forecasting future trends. Similarly, vegetated land surfaces may constitute a sink for trace gases and any changes in surface loss rates in both the past and future are needed for models to accurately represent the loss of trace constituents. Ultimately, interactive models which couple the atmosphere and the biosphere are needed.

4. Natural Hazards:

Since sulfur dioxide and ash are important products of volcanic eruptions, measurements of these products in the atmosphere following eruptions are important. They not only help shed light on the magnitude and characteristics of the eruption, but they are needed to help understand how the chemical and thermal state of the atmosphere may be altered following eruptions. These measurements can be made in essentially real-time by the TOMS instrument, and can be used operationally (see section VI.F).

B. Other Strategic Enterprises Within NASA

1. Aeronautics Enterprise

The close collaboration between MTPE and the Office of Aeronautics through its Atmospheric Effects of Aviation Project (AEAP), which studies the effects of subsonic and supersonic aircraft on atmospheric chemical composition and radiative properties, have been discussed already (see section II). An additional overlap has been through the Environmental Research Aircraft and Sensor Technology (ERAST) program. In addition to supporting the development of remotely piloted aircraft, which are expected to have great utility in the study of both tropospheric and stratospheric chemistry, the ERAST program has supported the development of six new *in situ* instruments for ultimate use on UAVs. In the interim, these instruments may be used on the NASA ER-2, the NCAR WB-57F, and/or balloons as part of UARP- and AEAP-sponsored field programs.

2. Scientific Research Enterprise

There is significant science overlap between MTPE science and that in the areas of Space Physics and Planetary Atmospheres. Interaction with the Space Physics Division centers on thermospheric and mesospheric science. Significant data on those regions of the atmosphere, as well as on the spectral output of the sun, have been obtained from MTPE-sponsored missions, including UARS and the ATLAS series of shuttle flights. The UARS GIP includes support for several teams emphasizing mesospheric, thermospheric, and solar science. The planetary atmospheres program in the Solar System Exploration Division conducts laboratory studies of photochemical and spectroscopic processes relevant to planetary atmospheres, and these studies closely parallel those supported by MTPE for the Earth's atmosphere. Finally, MTPE coordinates with the Office of Space Science in the organization of balloon campaigns so that deployment costs can be minimized.

3. Space Technology Enterprise

The closest interaction between MTPE and the Space Technology Enterprise will come through the New Millennium Program, in which the development of potential space-based instruments for studying the Earth will be developed. A number of candidate instrument concepts (and instrument/platform combinations) which could be used for the study of atmospheric chemistry are under consideration. There is also a tie through the Clark spacecraft, which will carry a small carbon monoxide-measuring instrument (microMAPS).

4. Human Exploration and Development of Space Enterprise

A small number of atmospheric chemistry measuring instruments will be flying on manned space platforms in coming years. The last planned flight of the SSBUV instrument was on the STS-72 flight in January, 1996, and the CRISTA/SPAS and MAHRSI instruments will fly on the Shuttle in 1997. In the longer term, the SAGE III instrument will be accommodated on the International Space Station. The MAPS instrument previously used on the Space Shuttle is to fly on the Russian MIR space station, and the Russian-German MIRIAM/DOPI instrument is likely to become an official part of the joint U.S.-Russian science program for the MIR platform.

V. Links to Other Organizations and Programs

NASA's research effort on ozone and atmospheric chemistry is closely tied in with that of other agencies of the federal government, that of foreign governments and organizations, as well as peer-led international scientific planning groups. In this section, those relationships are briefly summarized.

A. Other U.S. Government Agencies

Coordination of research efforts on ozone and atmospheric chemistry are carried out through a number of groups, including the Stratospheric Monitoring subgroup of the Office of the Federal Coordinator for Meteorological Services and Supporting Research (which NASA co-chairs with NOAA), the interagency working group on UV monitoring, and the Air Quality Research Subcommittee of the Committee on the Environment and Natural Resources.

Direct collaboration with other U.S. agencies includes the following:

1. National Oceanic and Atmospheric Administration

NASA's closest tie in atmospheric chemistry research has historically been with NOAA. In particular, the Aeronomy Laboratory and the Climate Monitoring and Diagnostics Laboratory of NOAA's Environmental Research Laboratories have been active participants in both the tropospheric and stratospheric aircraft experiments. They have contributed several critical instruments to the ER-2 for the stratospheric aircraft missions, and will be providing one for the OMS balloon campaign. Aeronomy lab personnel have served on the theory team for these missions, and served as project scientist for the AAOE, AASE I, and ASHOE/MAESA (as well as the upcoming POLARIS) missions. They have also provided crucial laboratory measurements on the photochemistry, spectroscopy, and thermodynamics of key atmospheric trace constituents. The WMO/UNEP assessments have historically involved close interaction between NASA and NOAA. NASA also cooperates closely with the National Environmental Satellite Data and Information Service (NESDIS) in the development of algorithms, calibration, quality control, and validation for the SBUV/2 instruments which fly aboard the operational NOAA meteorological satellites. NASA's SSBUV program has played a particularly important role in maintaining the calibration of the SBUV/2 instruments (both individually and as a series). NASA scientists collaborate closely with those from the National Meteorological Center for Environmental Prediction (NCEP) in studies of stratospheric temperatures and ozone distributions. Currently, NASA and NOAA personnel are engaged in discussions concerning possible ozone-measuring instruments to fly as part of the National Polar Orbiting Environmental Satellite System (NPOESS).

2. National Science Foundation

Closest interactions with NSF involve the National Center for Atmospheric Research (NCAR), which also provides aircraft instruments for the ER-2 and DC-8. NCAR participates in a variety of MTPE-sponsored modeling and data analysis efforts, including the UARS GIP and, most recently, the SAGE II Science Team. The NCAR atmospheric chemistry modeling group plays a critical role in the core model being developed by AEAP together with ACMAP.

3. National Institutes for Standards and Technology

NIST laboratory scientists play a significant role in carrying out laboratory measurements of atmospheric spectroscopic and photochemical processes, and also participate extensively in the biennial revision of the *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling* report.

4. Department of Defense

Close interaction is being developed with the Naval Research Laboratory (NRL), through its current flight of the Polar Ozone Aerosol Monitor (POAM) instrument and its planned follow-ons, including those for an inclined orbit (OOAM, 1997–98), and a polar orbit (POAM III, 1997–98). NRL also provides the SUSIM instrument on UARS (and ATLAS), as well as the MAHRSI instrument which flies on the Space Shuttle as part of the

CRISTA/SPAS payload. NRL scientists are also active in developing coupled two-dimensional models of the stratosphere and mesosphere, and closely interact with more stratospherically-oriented modelers, especially at the Goddard Space Flight Center. NASA will also be collaborating with DOD supported scientists at the Johns Hopkins University Applied Physics Laboratory associated with the Midcourse Space Experiment (MSX) launched in the spring of 1996. In particular, there is an ultraviolet instrument (UVISI) instrument aboard MSX that will serve to demonstrate potential new technology which could be useful in a future class of ozone-measuring instruments.

5. Environmental Protection Agency

EPA and NASA interact on a regular basis to ensure that NASA's efforts on stratospheric ozone are useful to policy makers and that scenarios used by NASA's modelers for both past and future emissions of CFCs and related molecules are accurate. EPA (together with DOE and NOAA) provides leadership for NARSTO, to which NASA is a signatory agency.

6. Department of Energy

DOE, through its atmospheric chemistry program, has significant overlap with NASA. DOE recently inaugurated its own atmospheric ozone program, including among other activities a reanalysis of SAGE data. The Lawrence Livermore National Laboratory is serving as the host institution for the Core assessment model being developed by AEAP with ACMAP participation.

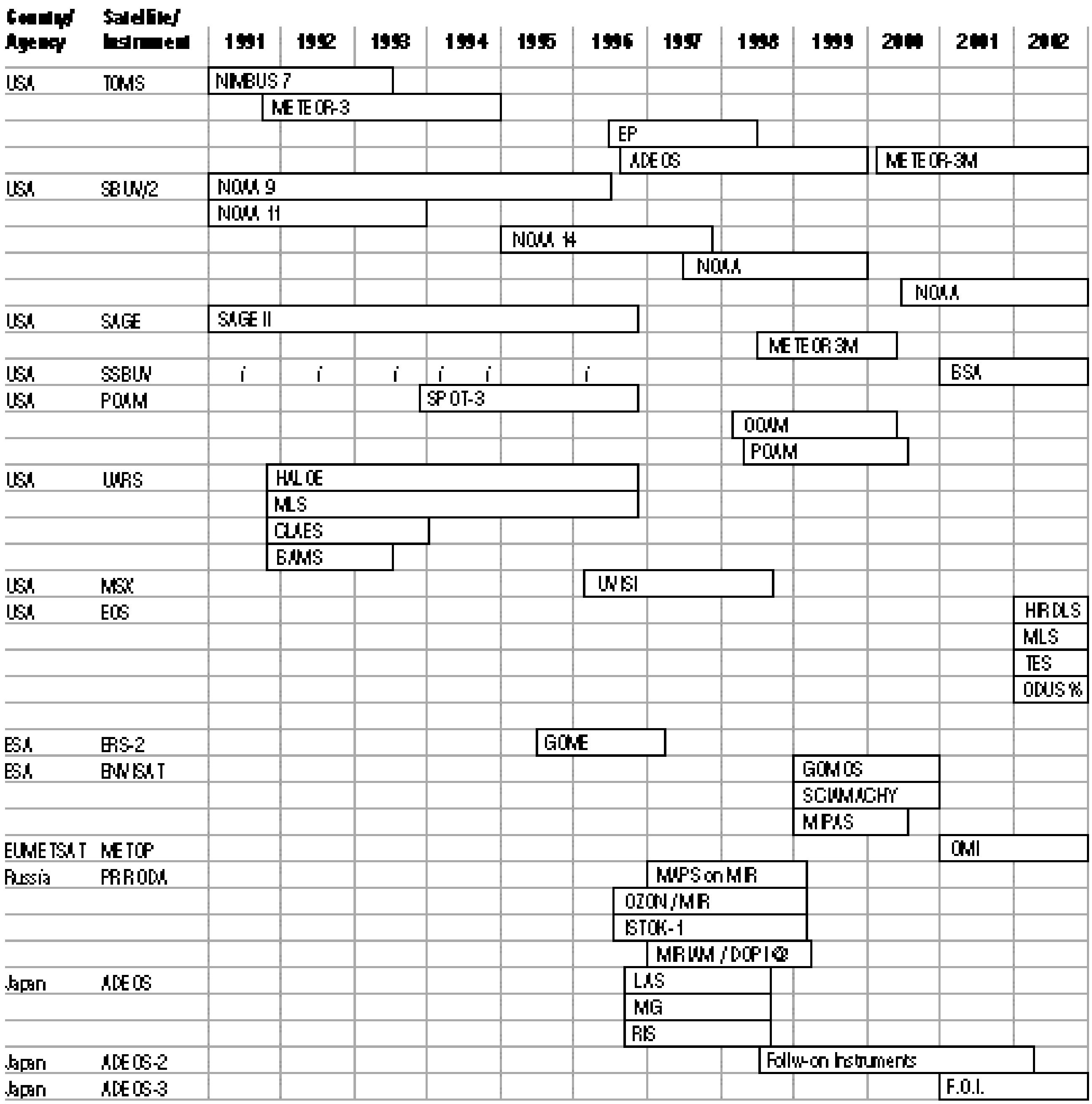
B. International Bodies

NASA's modeling activities are closely coordinated with their foreign counterparts. Much of this cooperation has been carried out as part of the WMO/UNEP and IPCC assessments. In particular, the WMO/UNEP assessment brings together several hundred scientists from around the world to review data, prepare the chapters, and provide peer review for the report. NASA personnel and grantees have been intimately involved in all stages of this effort for well over a decade, and work with others to prepare detailed summaries of issues of atmospheric relevance as needed to support the assessment process.

As more nations of the world introduce space-based measuring programs, NASA's participation in international cooperative activities will only increase. For example, space-based instruments which measure atmospheric ozone (and in many cases, related trace constituents) are planned for launch by several foreign partners over the next few years. A summary of past, present, and future space-based ozone-measuring instruments is given in Figure 5-6. These include the European Space Agency's (ESA's) Global Ozone Monitoring Experiment (GOME) launched aboard the ERS-2 satellite this past April, the ISTOK-1 and OZON-MIR instruments launched on the PRIRODA module for the Russian MIR space station in spring 1996, the German/Russian MIRIAM/DOPI instruments scheduled to be launched to PRIRODA in the fall of 1996, the IMG, ILAS, and RIS instruments to be flown on the Japanese ADEOS spacecraft in summer 1996, the SCIAMACHY, GOMOS, and MIPAS instruments to be launched aboard the European ENVISAT in 1999, and the Chilean-built OLME instrument, planned for launch on their FaSAT Bravo satellite (the launch of the FaSAT Alpha satellite, which contained the first version of this instrument, was a failure).

In the long-term, cooperation of NASA, NOAA, our foreign partners, and the international science community are all needed if an effective space-based ozone monitoring strategy is to be created. The highest priority is that a continuous set (covering both total ozone and vertical profile, including some direct measurement of tropospheric ozone) of high quality measurements be made. The partitioning of that effort among the possible contributors, both through operational programs (U.S. NPOESS, EUMETSAT

Space-Based Ozone Measuring Instruments



Notes: % Japanese-provided instrument; @ Joint Russian-German built instrument.

Fig 5-6

METOP) and research programs (e.g., U.S. EOS, Japanese ADEOS and its successors), needs to be worked out. Coordination and utilization of the whole array of available balloon-, aircraft-, and ground-based sensors, along with supporting research and modeling/ analysis activities, are also needed to most efficiently advance our scientific understanding of the atmosphere.

C. Peer-Led Science Planning Groups

The two peer-led scientific planning groups most relevant to NASA's ozone and atmospheric chemistry research are the World Climate Research Program, through its Stratospheric Processes and their Role in Climate (SPARC) subgroup, and the International Geosphere-Biosphere Programme (IGBP) through its International Global Atmospheric Chemistry (IGAC) program.

Plans are underway through a subgroup being set up under SPARC, together with the World Meteorological Organization and the International Ozone Commission, to try to coordinate future space-based ozone measurements. Calibration and validation plans need to be established. It is likely that the NDSC will provide a critical role in the on-orbit validation of all these spacecraft. NASA has the potential to play a fundamental role in the development of calibration plans for ozone instruments, especially in the ultraviolet.

Under the IGAC program, there are several activities, including the Global Emissions Inventory Activity (GEIA), Global Observations of Atmospheric Chemistry (GLOCHEM), and Global Integration and Modeling (GIM). The recent merger of the International Global Aerosol Program (IGAP) into IGAC has led to the formation of IGAC-FAA (Focus on Atmospheric Aerosols) which will also provide a good coordinating mechanism for NASA's chemistry-related aerosol research.

Fig. 5-6 (left): Timeline showing past, present, and projected future space-based ozone measurements organized by launching nation/agency, showing platforms and instruments. Potential instruments, or known instruments with launch information unknown are shown at the bottom. Dates are approximate.

VI. Future Emphases and Connections

NASA's ozone program will likely change in an "evolutionary" way over the next decade. The continued thrust will be to reduce uncertainties in our knowledge of atmospheric processes, our quantitative understanding of long-term atmospheric changes, and our ability to forecast the future chemical state of the atmosphere using computational models. While in the past NASA's program in atmospheric chemistry was very strongly stratospherically-dominated, the efforts in stratospheric and tropospheric research are expected to become more equivalent in the coming decade.

These plans are indicated schematically in Figure 5-7 which shows a 10-year plan for NASA's ozone program, broken up according to the six approaches of the previous section. Of course, one cannot be too complacent in foreseeing the future—a 10-year plan produced just over a decade ago might have completely ignored the issue of polar ozone depletion, which was not discovered until 1985!

There are three areas where progress may be more than incremental, however. These arise from the projected availability of launches of newly-developed satellite instruments, new aircraft which provide opportunities for *in situ* and remotely-sensed measurements, and high performance computing equipment which will facilitate the construction and use of improved three-dimensional troposphere/stratospheric chemistry/transport models. Brief summaries of the impacts of these capabilities follow.

The launch of spacecraft in the EOS program, as noted in section III.E, will have a major impact on NASA's atmos-

10-Year Plan for NASA Ozone Program

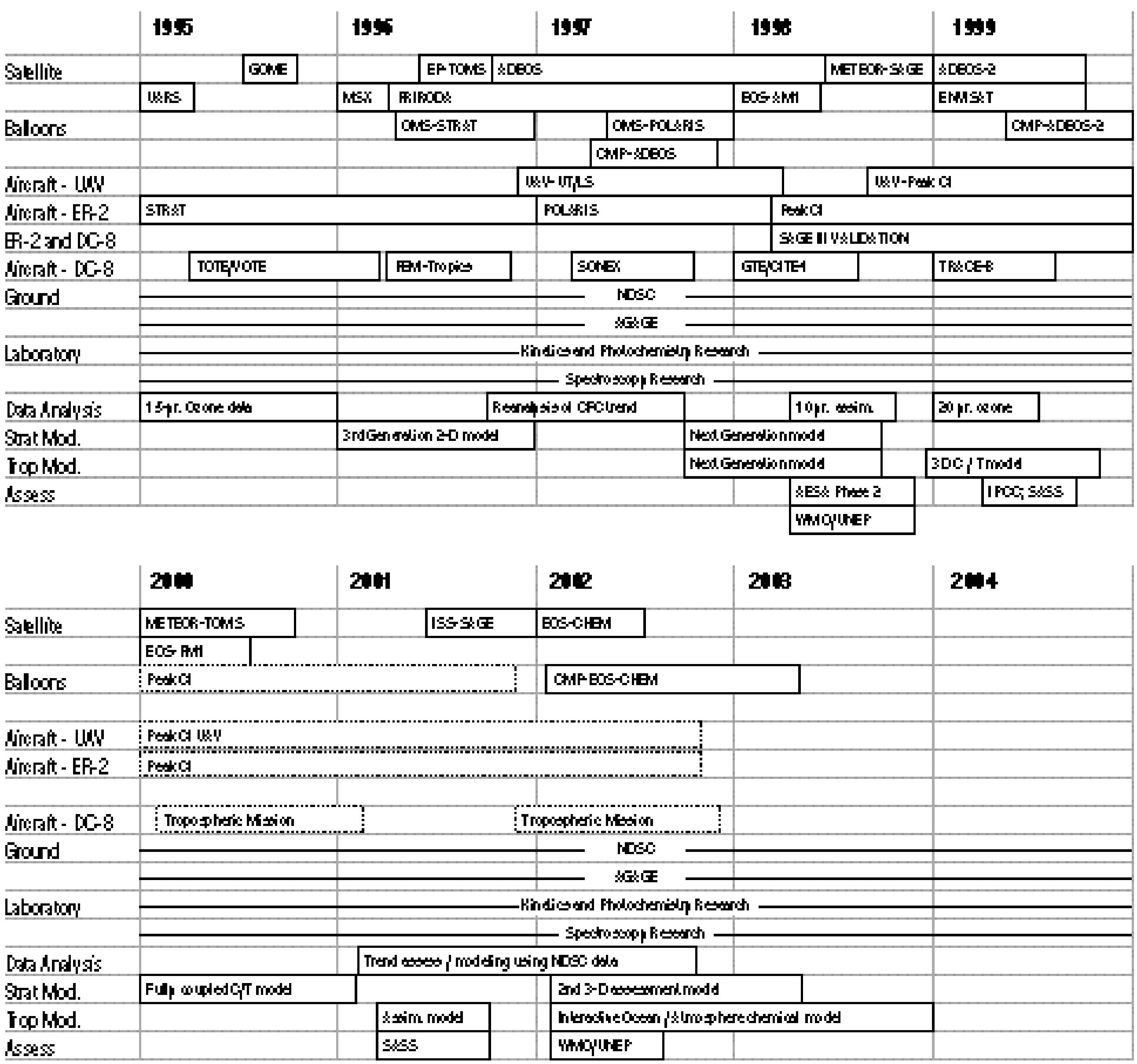


Fig 7-7

pheric chemistry program. Key data sets to come from these will include global measurements of vertically-resolved tropospheric carbon monoxide (as well as column integrated methane) from the Measurement of Pollution in the Troposphere (MOPITT) instrument on the first EOS spacecraft (EOS-AM) in 1998, measurements of stratospheric and upper tropospheric aerosols, ozone, and other trace constituents from SAGE III (launches in 1998 and 2001), and global measurements of most important trace constituents in the troposphere and stratosphere aboard EOS CHEM in 2002. Included in these will be the first-ever global measurements of vertically-resolved tropospheric ozone and its precursors from the TES instrument, extended global measurement of small-scale structure in stratospheric trace constituent distributions from the HIRDLS instrument, and extended global measurements of lower stratospheric OH from the MLS instrument.

New aircraft platforms, especially UAVs (see section III.D) will potentially provide opportunities for measurements at higher altitudes and with very different operational characteristics (e.g., longer flights) than with currently available platforms. Instruments for these aircraft are currently under development through the ERAST program (see section IV.B.1).

Finally, improvements in high performance computing (both hardware and computational and numerical algorithms) have the potential to allow for the use of three-dimensional coupled chemistry/transport models for the troposphere and stratosphere which would be impractical with current computing capability. Development of algorithms and combined modules for this work is currently supported through NASA's HPCC program. It is expected that the routine use of the core model being developed under AEAP (with ACMAP support and participation) hinges on the availability of this improved computing power.

Fig. 5-7 (left): 10-year plan for NASA ozone program, with different program elements organized according to six techniques in section III of this report.

There are also several new opportunities and initiatives which will be pursued under NASA's ozone and atmospheric chemistry program which represent changes in emphasis and/or direction from previously, however. These are summarized as follows:

A. Chemistry-Climate Coupling

NASA's ozone and climate research will be increasingly interactive. In the upper troposphere, ozone is a strong climate gas, but one whose distribution is controlled through a complicated set of chemical reactions (and which are closely tied to transport processes such as convection and stratosphere/troposphere exchange). In the lower stratosphere ozone depletion can also lead to reduced ultraviolet heating, and models must therefore simulate the chemistry (and aerosol behavior) there. Further, cooling of the global stratosphere expected due to increased carbon dioxide and reduced ozone can affect ozone destruction, especially through changes in reaction rates and changed formation of polar stratospheric clouds and aerosols. Such couplings are highly non-linear, and have the potential to lead to major effects if "threshold" behaviors are reached.

Other research has shown that tropospheric aerosols, especially those in the lower troposphere which form from oxidation of anthropogenically-generated sulfur compounds, may be important for climate. The formation of these aerosols is essentially chemically-driven, beginning with the oxidation of sulfur dioxide by hydroxyl, for instance. In the longer term ozone-oriented chemistry-climate models and radiatively-oriented models of atmospheric aerosols will likely become unified into more general "chemistry-climate" models. These will place enormous demands on computing capability, and progress in this area will likely rely on use of highly parallel computing equipment and specifically-designed algorithms. This is an issue for which close collaboration with NASA's High Performance Computing and Communications (HPCC) program is greatly desired.

An example of the implementation of this tie is NASA's recent selection of several tasks in this area as part of an augmentation of IDS activities of the EOS. Three major modeling efforts were selected, as well as several more process-oriented tasks which should facilitate the development of future coupled models.

Finally, there has recently been a recognition that the stratosphere can exert a significant downward forcing on the troposphere. A particularly interesting component of this forcing is that due to the large solar cycle associated with the absorption of short-wavelength ultraviolet radiation by stratospheric ozone, and the resulting small changes in circulation. Coupled troposphere-stratosphere transport models which include realistic representations of the dynamical feedbacks between stratospheric ozone, stratospheric circulation, and tropospheric circulation, will be needed for the downward control to be simulated.

B. Constituent Assimilation

Data assimilation has been a widely-used tool in the meteorological community. In data assimilation, observations and models are combined in a way to produce geophysically consistent and accurate global fields of temperatures, winds, and other parameters. The use of data assimilation has evolved far beyond its initial one to provide balanced initial conditions for numerical weather prediction. It now occupies a central role in atmospheric science in providing accurate daily global fields of numerous parameters.

In the future, data assimilation is likely to include trace constituents in addition to the meteorological parameters. Initial experiments assimilating nitrous oxide observations from UARS are showing the utility of the data assimilation process. In the short term, assimilation of ozone will be used to help improve short-term forecasts of ozone variability to improve UV exposure indices (this is collaborative work with NOAA). In the longer term, there are plans to assimilate several atmospheric trace species. This will be done in conjunction with the EOS program, which will provide global data on numerous trace constituents in the troposphere and stratosphere. The most straightforward application of constituent assimilation is to long-lived tracers, but application to ozone and ultimately intermediate-lived tropospheric compounds (such as carbon monoxide) is also planned.

C. Atmospheric Chemistry-Aerosol Interface

In the past, there has been little overlap between NASA's research on tropospheric aerosols, which have emphasized their radiative effects, and tropospheric chemistry, which has emphasized the oxidizing capacity of the free troposphere. In the foreseeable future, we see much more attention paid to the chemical processes which are responsible for formation of atmospheric aerosols, those which may occur on the surface of aerosols, and the connection between aerosol composition and radiative properties. This will likely involve a combination of laboratory and field experiments, as well as the inclusion of tropospheric aerosol distributions and properties into tropospheric chemistry/transport models (see section IV.B.1 above). As an example, both atmospheric chemistry and radiation measurements were part of the Aerosol Characterization Experiment (ACE) and the Tropospheric Aerosol Radiative Forcing Experiment (TARFOX).

There will also be increasing attention paid to maximizing the information on tropospheric aerosols which can be obtained from data sets which were originally developed for chemical purposes. For example, a good measure of tropospheric aerosol burden is now inferred from TOMS measurements, using a technique based on differences between albedo in two long wavelength reflectivity channels. This product needs to be carefully validated by comparison with surface measurements of optical depth. Measurements of aerosol profiles in the upper troposphere have been made using SAGE following development of an algorithm to separate aerosol-created opacity from that arising from clouds. Additional validation of this algorithm is needed.

Finally, there is a need for instruments which can make *in situ* aircraft measurements of the chemical composition of atmospheric aerosols. Work has begun on instruments to do this, and completion of these instruments remains a high priority of NASA's overall efforts in this area.

D. Atmosphere-Land and Atmosphere-Ocean Interface

Models provide an important integrative tool for using global measurements of atmospheric trace constituent composition and measurements of surface biogeochemical processes. Models may be especially useful in providing tests of the consistency of known information about surface production and destruction of trace gases, atmospheric destruction, and atmospheric transport. This approach has been used in the past with good success in studying the distribution of CFCs and related molecules in the troposphere. This can include species produced both at the land surface, notably methane, as well as those produced and/or destroyed in the ocean, such as methyl bromide. A particular near-term focus may be on whether or not one can use a combined global atmospheric chemistry/transport model with a land biogeochemistry model to understand the interannual variability in the growth rate of atmospheric methane. Later on, similar models with improved representation of the atmosphere/ocean interface, as well as of biological and chemical processes which result in the production and destruction of methyl bromide may be used to help simulate that compound's behavior.

E. Air Quality

NASA's research on tropospheric ozone has focused on the global atmosphere, with an emphasis on remote areas of the troposphere. This has helped differentiate NASA's research from that of EPA and DOE, which are typically focused on polluted areas, especially those in the U.S. There has been increasing attention in the past few years on how developed areas influence ozone distributions in remote areas, and such efforts are expected to continue, especially as the importance of understanding background ozone concentration increases. In particular, the possibility exists that significant changes in background ozone concentration will have an effect on local/regional air quality with possible repercussions for achieving mandated standards.

NASA's expertise in modeling, remote sensing, laboratory measurements of rates of fundamental processes, and in aircraft-based *in situ* and remote measurements will come to bear on this problem. NASA will also be prepared to make unique contributions to the North American Research Strategy for Tropospheric Ozone (NARSTO) effort recently initiated by the Air Quality Research Subcommittee of the Committee on the Environment and Natural Resources. One potential area for specific NASA contribution to NARSTO is evaluation of the role which downward transport of stratospheric or upper tropospheric ozone has on local/regional ozone budgets; discussions have begun on the possibility of NASA organizing or co-organizing a workshop on this subject for NARSTO.

Methods to infer tropospheric ozone from space-based measurements, either directly from TOMS data or from the residual between TOMS and SBUV/2 or TOMS and SAGE data, have been carried out with some success. The TES instrument will provide significant information on tropospheric ozone and other constituents in the post-2002 time frame. Additional research to further develop these techniques and to help define under what conditions they are expected to have use, will continue over the next few years. It is possible that simple instruments which can directly measure tropospheric ozone will be developed under the NMP and/or ESSP programs.

Finally, it is important to note the natural tie between regional and global atmospheric models, especially in areas of surface sources and deposition of trace species. Both global and regional models need spatially and temporally resolved fluxes of trace constituents. Similarly, removal of soluble species, especially sulfur and nitrogen oxides, from the stratosphere in global models will be carried out by the same processes that lead to acid deposition. Modules for these processes may be common to both the air quality and global change communities, and data bases must be accessible to both. To help support efforts in this area, especially on surface sources, NASA plans to participate in the Global Emissions Inventory Activity (GEIA) of the IGBP IGAC project, under which spatially and temporally resolved emission inventories for oxides of nitrogen and sulfur, as well as organic compounds, are being developed.

F. Applications

NASA scientists have recently shown that a relatively simple model of ultraviolet radiative transfer, including cloud effects, can provide a good representation of surface ultraviolet flux given total ozone measurements. Plans are to make daily maps of inferred surface ultraviolet radiation available on a regular basis following the launch of Earth Probe and ADEOS TOMS, and retrospective studies to produce information about past surface UV flux are underway. The stratospheric ozone-UV flux relationship may be used together with the stratospheric ozone data to support the "UV-forecasting" network of NOAA and EPA.

The Federal Aviation Administration (FAA) and NASA have signed a memorandum of understanding to consider the use of TOMS ozone data by the FAA to help plan more efficient routing of jet aircraft. Although the theoretical basis for these efforts is not well established, there is anecdotal evidence suggesting that TOMS data can help "find the jet stream" in near-real time, and that more efficient aircraft routes can be developed using TOMS data. The FAA also wants to use information on sulfur dioxide from TOMS to help pinpoint regions of volcanic cloud hazards in aviation, so that aircraft may be routed around these regions. NASA is supporting the development of improved SO_2-algorithms for TOMS, and these will be provided to the FAA.

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APPENDIX 5-1 – Measurement Capabilities for Atmospheric Trace Constituents

KEY: I = *In situ* P = Profile C = Column ( ) = Planned

	AGAGE	NDSC	DC-8	ER-2	Balloon	Shuttle	Satellite*	Planned Satellite
P,T		P	P	I	I	P	P	P
Aerosols		P	P	I, P	I		P	P
Winds				I	I			
O_3		P, C	I, P, C	I	I, P	P, C	P, C	P, C
H_2O		P, C	I, P, C	I,P,C	I, P	P	P	P
CO_2	(I)		I	I	I, P	P		
N_2O	I	P, C	I, P	I	I, P	P	P	P
CH_4	I	C	I, P, C	I	I, P	P	P	P, C
CO	I	P, C	I	I	P	P	P, C	
CFC-11	I	C	I	I	P	P		P
CFC-12	I	C	I	I	P	P		P
CFC-113	I		I	I	P			
HCFC-22	I	C	I, P	I	P	P		
HCFC-123	I		I	I				
HCFC-142b	I		I	I				
HCFC-141b	I		I	I				
CH_3Cl	I		I	I		P		
CCl_4	I		I	I	P	P		
$CHCl_3$	I		I	I				
CH_2Cl_2			I	I				
CH_3CCl_3	I		I	I				
COF_2		C	P	P	P			
CF_4	I		C	P	P			
C_2H_6		C	I	I		P		
CH_3Br	I		I	I				
SF_6	I	C		I	(I)	P		
NO		C	I	I	I, P	P	P	P
NO_2		C	I	I	I, P	P	P	P, C
NO_3								P
HNO_3		C	I, P		I, P	P		P
$ClNO_3$		C	C	(I)	P	P		P
N_2O_5			I		P	P		P
HNO_4			I			P		

	AGAGE	NDSC	DC-8	ER-2	Balloon	Shuttle	Satellite*	Planned Satellite
PAN			I					
NOy			I	I	I	P		
HCl		C	P, C	I	P	P	P	P
HF		C	P, C		P	P	P	
HBr								
OH		C	P, C	I	I, P			P
HO_2			P, C	I	I, P			
H_2O_2			P, C		P			
HDO			P, C		P		P	
ClO		P, C		I	I, P		P	P
OClO		C						P
BrO		C		I	I			
HOCl			C		P			
HCN		C	P, C		P	P		
SO_2			I			P	C	C
DMS			I					
OCS		C	I, P, C		P		P	
UVB Flux		C						
UV Flux			I	I				
Halon-1211			I	I				
H_2				I	P			
O_2			C		P, C			
N_2			C		P, C			

* Currently operating, NASA-supported instruments/satellites

† NASA-supported instruments/satellites

Appendix 1
MTPE Core Science Program Cross-cut

P=Primary; C=Contributing

	Land-Cover and Land-Use Change Research	Seasonal-to-Interannual Climate Variability and Prediction	Natural Hazards Research and Applications	Long-Term Climate: Natural Variability and Change Research	Atmospheric Ozone Research	Inter-disciplinary Earth System Science Research
ATMOSPHERIC DYNAMICS & REMOTE SENSING		P	C	P		C
GLOBAL MODELING AND ANALYSIS	C	P	C	P	C	C
RADIATION SCIENCE	C	P		P	C	C
UPPER ATMOSPHERE RESEARCH		C			P	C
TROPOSPHERIC CHEMISTRY	C				P	C
ATMOS. CHEMISTRY MODELING & ANALYSIS		C		C	P	C
LAND-COVER & LAND-USE CHANGE	P	C	C	C	C	C
TERRESTRIAL ECOLOGY PROGRAM	P	C	C	C	C	C
LAND-SURFACE HYDROLOGY	C	P	C	C		C
PHYSICAL OCEANOGRAPHY & MODELING		P		P		C
BIOLOGICAL OCEANOGRAPHY		C		C		C
POLAR RESEARCH	C	C	C	P		C
NATURAL HAZARDS	C	C	P			C
GEOLOGY	C	C	P	C		C
GEODYNAMICS, GEOPOTENTIAL FIELDS		C	P	C		C
GLOBAL DATA INTEGRATION & VALIDATION	C	C	C	C	C	C
RESOURCE VULNERABILITY RESEARCH	C	C	C	C		C
EOS INTERDISCIPLINARY SCIENCE	P	P	P	P	P	P

Appendix 2
MTPE Science Division Core Program Descriptions

Atmospheric Chemistry Modeling and Analysis Program

GOAL:
To improve our understanding of the distribution of chemically and radiatively active trace constituents and aerosols in the troposphere and stratosphere at regional to global scales, through the development of computational models representing atmospheric chemistry and transport processes, and by model-based analysis and interpretation of atmospheric constituent and dynamical data.

STRATEGY:
To develop models of atmospheric chemistry and physics for both the troposphere and the stratosphere, and to interpret atmospheric trace gas and aerosol data, emphasizing the characterization of spatial and temporal variability and distinguishing between natural and anthropogenic origins of this variability.

ELEMENTS:

- Develop and evaluate computational models of tropospheric and stratospheric chemistry and transport for studies of the current atmosphere, as well as for retrospective and predictive studies, and to provide planning and data analysis for field campaigns.

- Develop and evaluate models of stratospheric and tropospheric aerosol and stratospheric cloud formation and their chemical and physical effects.

- Characterize the variability of atmospheric trace constituent and aerosol concentrations and quantify their dependence on natural factors such as the solar cycle, volcanic eruptions, the quasi-biennial oscillation, El Niño Southern Oscillation, and particle precipitation events, and human activities, such as chlorofluorocarbon emissions and other industrial activities.

- Develop coupled chemistry-climate models which will simulate the combined effects of greenhouse warming and ozone depletion.

- Develop modeling tools for the inference of sources and sinks of trace gases at the Earth's surface and in the atmosphere.

- Extend analysis of current or historic satellite data to obtain and validate research products and support analysis of non-NASA data sets.

- Develop methods for inferring amounts of surface UV radiation and absorbing tropospheric aerosols from space based data.

- Provide modeling and analysis support for externally sponsored assessments such as WMO/UNEP Ozone Assessment and the IPCC Climate Change Assessment, as well as for the assessment of the Atmospheric Effects of Aircraft Program.

Atmospheric Dynamics and Remote Sensing Program

GOAL:

To develop an improved understanding of the physical processes important in establishing the circulation of the atmosphere on all scales, ranging from the cloud, regional and mesoscale to the global scale. This includes not only a comprehensive understanding of the distributions and variations of mass, energy, momentum and water vapor in the troposphere on all scales, but also a complete understanding of the coupling between the dynamical and thermodynamical processes with the hydrological and radiative processes.

STRATEGY:

To accomplish these goals it is necessary to monitor the critical physical variables that characterize the state of the atmosphere. Therefore the research programs pursued include the development of ground, airborne and space-based remote sensing techniques, participation in field experiments to obtain comprehensive data sets, and advanced process modeling studies such as interscale energy transitions; and development of parameterizations for moist convective systems, frontal zones, internal gravity waves, clouds and radiative transfer.

ELEMENTS:

- ◆ *TRMM Science:* TRMM (Tropical Rainfall Measuring Mission) will provide the first and most accurate observations of rainfall on a global scale ever made. This program element is in place to ensure breakthroughs in dynamical meteorology as well as in climate modeling resulting from the TRMM data.

- ◆ *Remote Sensor Development:* This element includes the development and refinement of: ground and airborne lidars for measurement of temperature, moisture, pressure and wind velocity profiles; airborne radars for measurement of precipitation and cloud properties; and microwave radiometers for surface imaging and the measurement of moisture, temperature and precipitation. All these activities are closely related to the development of ongoing or planned satellite sensors.

- ◆ *Data Analysis:* This involves satellite data analysis, and calibration and validation of this data. This also involves participation in international and multi-agency coordinated field programs like TOGA-COARE, CAMEX and GCIP and analysis of data obtained during these campaigns.

- ◆ *Theory and Numerical Modeling:* Modeling undertakings of interest include study of mesoscale phenomenon and interscale energy transitions; and development of parameterization for moist convective systems, frontal zones, internal gravity waves, clouds and radiative transfer. The global distribution of rainfall is critically important in monitoring the global energy and water cycle. The heat released into the atmosphere by the phase change from vapor to liquid and subsequent fallout, i.e., precipitation, is an important element in the energy exchange in the general atmospheric system and critical in understanding the evolution of atmospheric systems from convection to cyclones.

Atmospheric Effects of Aviation Program

PROGRAM NOTE:
Program is collaborative effort between NASA Office of Aeronautics (OA) and Office of Mission to Planet Earth (OMTPE). OA funds are interwoven with, and serve to augment and/or redirect ongoing OMTPE R&A activities.

GOALS:
Develop a scientific basis for assessment of the impact of future subsonic, and potential supersonic, aviation on atmospheric ozone levels and global climate. Program focus is on commercial aircraft cruise emissions.

STRATEGY:
Promote advancements in the conceptual understanding and computational model representations of upper troposphere/lower stratosphere (UT/LS) processes and aircraft wake and plume processes. Improve input databases for models, specifically those for operational aircraft scenarios, photolysis rates, chemical reaction rates, and source gas emissions from the Earth's surface. Denote and quantify, where possible, uncertainties in the conceptual understanding and model representation of atmospheric processes related to aircraft impacts.

ELEMENTS:

1. *Supersonic Aircraft*

a. Extend observational database for long-lived stratospheric tracers and radicals to include a number of seasonal cycles and undersampled regions of the atmosphere, notably the summer high latitudes and tropics.
b. Systematically develop 3-D chemical-transport models for use in aircraft assessment calculations through algorithm development and comparison with observations.
c. Further characterize, through laboratory and atmospheric observations, the composition and temporal evolution of aircraft exhaust aerosols in the wake/plume regime and the composition and microphysics of polar stratospheric clouds (PSC's). Include computational algorithms for these processes in assessment models.

2. *Subsonic Aircraft*

a. Establish, through atmospheric observations, the fraction of UT NOx that can be attributed to aircraft emissions and determine the response of ozone to changes in ambient NOx levels.
b. Through combination of process models and observations assess the potential for air traffic emissions to impact the atmospheric radiative balance through occurrence of contrails, alteration of naturally occuring cirrus cloud properties, enhancement of ambient aerosol optical depth, and removal of upper tropospheric water vapor.
c. Systematically construct and scrutinize 3-D chemistry and climate models for assessing the impact of commercial aviation.
d. Develop accurate global inventories of subsonic aircraft exhaust species.

Global Modeling and Analysis Program

GOAL:
Use models and model-assimilated data sets to assess global climate system variability and trends on seasonal-interannual through century time scales.

STRATEGY:
- ◆ Develop, improve, and test global atmospheric climate models and their couplings to models of other parts of the Earth system, and use them to diagnose and predict climate variations and trends, with the objective of providing analytic and predictive capability for assessments of global climate and Earth system behavior.

- ◆ Develop, improve, test, and assist in implementing a near-real-time model-driven data assimilation system that will have the capability of ingesting EOS and other remotely sensed observational data along with conventional data, with the objective of providing the best possible synthesis of observational information and model skill, in the form of research quality climate data sets, for community use.

ELEMENTS:
- ◆ Global model development and improvement, including model numerics, dynamical cores, radiation algorithms, and coupling of atmospheric GCM with other climate system components, for climate system research and for dynamic data assimilation.

- ◆ Development and testing of parameterizations of physical, chemical, and biological processes in models, proceeding from process-oriented models and algorithms to representations suitable for global climate system models.

- ◆ Development of improved methodologies for dynamic four-dimensional model-based data assimilation, including objective analysis methods based on Kalman filter theory, efficient data quality control procedures, dynamic initialization of assimilating model, and variable grid procedures for regional-scale assimilation.

- ◆ Diagnostic and predictive studies of the global climate using models and model-assimilated data sets, including evaluation of model performance, evaluation of assimilated data sets, use of assimilated data sets to study climate system energetics and climate trends and variations, and use of climate system models together with data sets to simulate past climate and predict future climate states.

Geodynamics Program

GOAL:

The Geodynamics Program is concerned with the development of science and technology related to the dynamics of the solid Earth and its interaction with the oceans and atmosphere. Expenditures are approximately equally divided between global change and natural hazards research. This program includes the development of geodetic techniques to measure deformation of the solid Earth including GPS, VLBI and SLR technology. Applications of the geodynamics technologies are strongly interdisciplinary and in some instances have demonstrated strong commercial benefits. Approximately 60 percent of the funding is allocated to the development, deployment, and operations of geodetic systems. The program supports this effort on three levels: (1) the development of technology, (2) the deployment and operation of field systems, and (3) the support of theoretical and analysis efforts. NASA developed the space geodetic techniques which is now widely accepted as some of the most promising technologies in natural hazards mitigation. Recent program cuts are placing a severe strain on this program and its international collaborations.

STRATEGY:

- Observe, understand and predict the dynamics and evolution of the Earth's lithosphere in order to mitigate the danger of earthquakes, understand land subsidence, locate and access natural resources with time scales of hours and longer.

- Observe and understand the dynamics in the Earth's orientation and rotation as a comprehensive indicator of Earth System Dynamics including paleoenvironment, oceanic and atmospheric circulation, internal core and mantle motions, extraterrestrial forcing functions with time scale of hours and longer.

ELEMENTS:

- Develop, operate global and regional geodetic networks;
- Develop GPS, VLBI, SLR technology and analysis;
- Support DOSE Dynamics of the Solid Earth Science Program;
- Maintain and improve terrestrial and celestial reference frames;
- Partnership with USN and NOAA in National Earth Orientation Service;
- Support development of Topography program; and
- Support development of GPS atmospheric occultation technology.

Geology Program

GOAL:

The overall goal of the Geology program is to improve our knowledge of the formation and evolution of the Earth's surface and continental crust, its interaction with the atmosphere, hydrosphere, and biosphere, and the processes responsible for short- and long-term changes to the Earth's surface and crust, including those responsible for natural hazards.

STRATEGY:

The overall strategy of the Geology Program is to focus on scientific understanding. Interdisciplinary investigations and international collaborations are encouraged. The program organizes much of its research around major campaigns involving field and aircraft deployments as well as individual field investigations. Because the program is oriented toward understanding processes, study sites are not limited to a particular geographic area but are distributed globally and usually represent the best place possible to study that particular phenomenon. In pursuit of these objectives, the program funds studies utilizing observations from laboratory-, field-, aircraft-, and satellite-borne remote sensing systems, funds the development of airborne instruments that are prototypes of candidate flight projects, funds engineering feasibility studies (Phase A and pre-Phase A) of potential flight projects, and funds modeling activities. Visible, infrared, thermal infrared, and microwave wavelengths form the primary measurement capability, including digital topographic data collected in the microwave (SAR) and near infrared (laser) parts of the electromagnetic spectrum. The program makes extensive use of existing aircraft and satellite sensor capabilities, including NASA's Airborne Visible and Infra-Red Imaging Spectrometer (AVIRIS), Thermal Infrared Multi-Spectral Scanner (TIMS), Airborne Synthetic Aperture Radar (AIRSAR)/Topographic Synthetic Aperture Radar (TOPSAR), and Laser Altimeters--all developed with support from this Program-- as well as satellite-borne systems such as Landsat, Satellite Pour l'Observation de la Terre (SPOT), ERS-1/2, JERS-1, RADARSAT, SIR-C/X-SAR, and Total Ozone Mapping Spectrometer. Satellite data are the only practical means of conducting such studies on regional scales or intercomparing results from disparate regions. Field-based experiments and observations of geologic processes are also a critical and necessary component of the program. The modeling of geologic processes is a key to understanding processes that are not observable on short time scales.

ELEMENTS:

- ◆ To map, characterize, and analyze features of the land surface to understand the interaction of aggredational and degredational processes of the Earth's systems related to development of the landscape and assess the effects of global environmental changes upon these features.
- ◆ To observe and monitor the structure and deformation of the Earth's surface to understand, assess, and mitigate the affects of geologic hazards, and to understand the formation and evolution of continental crust.
- ◆ To observe, model, and understand volcano-atmosphere interactions and assess the influence of volcanic activity on past, present and future global and climate change.
- ◆ To contribute to the development and validation of a baseline from which to assess current and future trends of global change, utilizing observations of the geologic record and modeling of geologic data.
- ◆ To measure at unprecedented levels of accuracy, and monitor temporal changes in, the topography of the Earth's surface and ice caps in order to study the processes of topographic evolution, land subsidence, and mitigate natural disasters.

Geopotential Fields Program

GOAL:

Two of the fundamental characteristics of matter are its density and its magnetic moment. The time rate of change in the gravity and magnetic fields are used to determine internal structure, composition and dynamics of the Earth, the mass flux within the atmosphere, cryosphere, hydrosphere, and lithosphere, as well as the fundamental processes which generate and maintain the geomagnetic field. One of the highest rated priorities of basic research in planetary and Earth science is an understanding of generation mechanism for the Earth's geomagnetic field. Both the gravity and magnetic fields are crucial data sets for global navigation and precision orbit determination of satellites. NASA through its collaboration with other national agencies leads in the development of the global gravity and geomagnetic field models for scientific and operational applications.

The Geopotential Fields Program and its predecessors have continued to develop the most advanced spacebased techniques available to measure the gravity and magnetic fields and their time variations. International collaborations such the Ørsted, Sunsat (mid FY 1997 launch) and SAC-C (FY 1999 launch) programs have been developed to utilize these technologies within severe budget constraints. NASA is uniquely poised among the U.S. agencies to develop and analyze the global geopotential fields. However, recent program cuts are placing a severe strain on this program and its international collaborations.

STRATEGY:

- Observe and understand the static and dynamic components of the Earth's gravity field as a means of detecting lithospheric and mantle structure and dynamics, cryospheric and hydrological mass flux, atmospheric circulation with time scales of months and longer.

- Observe and understand the dynamics of the Earth's magnetic field as a means of characterizing the core processes which generate the Earth's main magnetic field, the mechanisms leading to a magnetic field polarity reversal, and the structure, composition, and evolution of the mantle and lithosphere, and of assessing natural mineral resources with time scales of months and longer.

ELEMENTS:

- Develop measurement strategies and sensors for space-based measurements;
- Superconducting Gravity Gradiometer;
- Satellite to Satellite Tracking;
- Advanced spaceborne GPS receiver and Chipsat constellation;
- Vector helium magnetometer;
- International geopotential missions e.g., Ørsted, SAC-C, Sunsat, Chipsats; and
- Global modeling and data analysis.

Global Data Integration and Validation

GOAL:
To support the interdisciplinary interpretation of remote-sensing data from a variety of U.S. and foreign satellites in order to validate atmospheric remote sensing algorithms and to study the time and space variations of the derived geophysical parameters.

STRATEGY:
To acquire appropriate satellite and *in situ* data to validate algorithm performance in regional-global intercomparisons and field experiments for the study of physical interactions between the atmosphere and the land, ocean or ice surfaces below; to refine the remote sensing algorithms until their outputs serve as base environmental states and as measures of the natural variability of specific parameters; to provide the determined environmental states, variability, and trends to models for characterizing model performance and validating retrospective model runs to the present; to determine the variability of atmospheric moisture, energy and water cycles, surface fluxes from the oceans, changes in water vapor radiative forcing and establish remote measurement capabilities for difficult variables like precipitation, cloud liquid water, water vapor varying with height, and in-cloud particle type effects; and to contribute to assessments of global and regional variability of atmospheric water source availability.

ELEMENTS:

- *Validation:* Precipitation algorithms, Pathfinder algorithms, temperature anomalies, moisture distributions and fluxes, ocean surface wind speeds, EOS sensors.

- *Variability evaluation:* Time and space variation of temperature, moisture, precipitation; global and regional maps and energy/water cycles; interannual changes and anomalies for derived parameters; trends; intercomparison with model outputs; prediction verification; regional projects.

- *Physical Interpretation of Variability:* Natural background states; moisture variable climate forcing; air-sea interactions; energy/water cycle changes; interaction mechanism determination.

- *Assessments:* Middle-East Water Assessment, GCIP, Mid-Pacific Region, Natural Hazards; anomalies.

Land-Cover and Land-Use Change Program

GOAL:

To develop the capability to perform repeated global inventories of land-cover and land-use from space, and to develop the scientific understanding and models necessary to evaluate the consequences of the observed changes.

STRATEGY:

Develop methods, techniques, and conduct research to evaluate impacts and the consequences of land-use change, establish ways to quantify them, and develop the capabilities to explore alternative land-use and monitoring strategies. The program will consist of a combination of satellite and field-based studies. The broader challenge of accurately accounting for land-use and land-cover change and the underlying research to interpret it will require a partneship with many scientific and natural resource management institutions around the world. Emphasis will be on the regions of the world currently undergoing the most stress and where stresses from human activities are sure to increase the most rapidly.

ELEMENTS:

- Develop satellite-based methods and techniques to identify the current distribution of land-cover types and track their conversion to other types.

- Investigate the consequences of intensified management of agricultural and agroforestry systems, particularly in the tropics and sub-tropics, and measure longer-term, *in situ* degradation of forested ecosystems.

- Develop techniques to incorporate land-cover and land-use change into existing biogeochemical and biophysical models.

- Develop interactions with Climate and Biodiversity Convention related country case studies assessing the extent and impacts of land-use change.

- Develop a series of reports that identify the consequences of land-use change in globally important areas of rapid change. Initial focus on land conversion in the Amazon Basin, land conversion and forest degradation in Southeast Asia, land conversion and savanna burning in Central and Southern Africa, boreal forest change in Russia, and regional case studies in the U.S.

- Develop and maintain strong links to Pathfinder data development, future field campaigns, Earth system modeling, developing technologies for land-cover identification (e.g., Lewis and Clark missions), and other U.S. and international research programs.

Land Surface Hydrology Program

GOAL:
To develop a predictive understanding of the role of water in land-atmosphere interaction and further the scientific basis of water resources management.

STRATEGY:
Develop process models for describing mesoscale coupling of atmospheric motion and the exchange of water, energy and momentum at the land surface; develop new or improved technology and techniques for measuring hydrologic variables and seek new applications to hydrologic problems; and formulate new theories about the role of land-atmosphere interactions in regional and global climate.

ELEMENTS:

- Develop the scientific basis for observing and modeling large-scale soil moisture dynamics, including devising analytical and numerical methods for describing the heterogeneity of soils, vegetation, and precipitation as well as the role of topography; developing remote sensing techniques for surface soil moisture; and applying modern data assimilation techniques to large-scale models of soil moisture dynamics to optimize the use of remote and *in situ* observations pertaining to the land–atmosphere interface and all components of the continental water balance.

- Develop regional coupled meteorological-hydrological models for future water resources planning and management and as tools for improving the performance of global models in terms of regional specificity and accuracy and their seasonal and interannual variability.

- Develop techniques for monitoring changes in surface hydroclimate due to changes in land-cover and land-use using existing remote sensing measurements and operational meteorological data.

- Participate in field and numerical experiments, as appropriate, to improve the coupling of physical, biological, and chemical processes, as well as the methodology for model verification.

Natural Hazards Program

GOAL:

Natural hazards are inevitable manifestations of Earth processes but need not be inevitable disasters. NASA can assist society in reducing losses of life, casualties and property and reducing social and economic disruptions from future natural disasters. Our goal is to contribute to the scientific understanding of Earth processes and conditions that lead to natural disasters, apply NASA-developed, earth-science inspired technology to risk mitigation, transfer demonstrated technology to responsible federal and state agencies, and develop international conventions for timely exchange of space-based information relating to disastrous events.

STRATEGY:

Although the Natural Hazards Program will conduct research related to all natural hazards, the program's initial research emphases will be in select areas in disaster reduction where the technology pathway is understood and significant milestones may be anticipated within the decade. These are:

a. Characterization of the relationship between pre-, co-, and post-seismic regional surface deformation and seismic and/or volcanic activity through Global Positioning System dense array technology and acquisition and analysis of time series synthetic aperture radar interferometry (SARI).

b. Multi-faceted approach toward forecasting local and regional flooding and other regional consequences of seasonal-interannual climate variability (related MTPE enterprise) through retrospective studies, watershed modeling, incorporation of satellite-derived parameters such as topography, land cover, rainfall, soil moisture, snow cover (and water equivalent) and snow melt. Related to this is a longer-term research objective to develop understanding of the consequences of year-to-year climate variations on the occurrence of floods, monsoons, droughts, and the severity and frequency of storms.

This is the first year of formal funding of the Natural Hazards Program. Several workshops with academic and interagency participation will be held this year and feasible and appropriate recommendations will be included in a proposal solicitation planned for distribution in spring 1996. Several NASA Offices in addition to Mission to Planet Earth which currently support aspects of natural disaster reduction can contribute to a coordinated agency-wide Natural Disaster Reduction Program: Space Access and Technology, Management Systems and Facilities, Life Sciences, and Space Communications. There are literally dozens of tasks at various NASA centers and universities. Because NASA's ability to serve society in reducing natural disasters goes well beyond the boundaries of Mission to Planet Earth, this program must be developed in increasingly closer coordination with other Offices within NASA.

ELEMENTS:

There are four aspects to the NASA/MTPE Natural Hazards Program:

a. Understand Earth processes which can lead to natural disasters and improvement of risk assessment capability for vulnerable regions.
b. Utilize existing or planned technology to aid in understanding hazardous processes, risk assessment, and disaster characterization.
c. Establish relationship with disaster management practitioners.
d. Coordinate with all international space-based agencies' research, observation, and flight project development programs in natural disaster reduction.

Ocean Biology Program

GOAL:
To predict the ocean's biogeochemical response to and its influence on climate change; to predict variability in the structure of the phytoplankton community and its link with higher trophic levels as well as biogeochemical cycles; and to develop the scientific principles and information base required to understand the potential productivity of the coastal marine ecosystem.

STRATEGY:
The Ocean Biology Program has developed two streams of research to address these goals. The first stream focuses on the production and analysis of decadal-scale time series of phytoplankton biomass and productivity on a global scale. The second stream emphasizes the development of predictive models of the ocean ecosystem.

ELEMENTS:

◆ *Ocean Productivity:* Global ocean color observations offer the only global observations of marine plant biomass. Historical data includes global observations with the Coastal Zone Color Scanner (CZCS) and compilation of global *in situ* observations of biomass, primary production, particle fluxes, and marine and atmospheric optics. Between 1996 and 2001, seven ocean color satellite missions (SeaWIFS, OCTS, POLDER, MODIS (AM and PM, MISR, MERIS, and GLI) plus several more experimental missions are scheduled for launch which will privide routine ocean color data over large portions of the global ocean. A special NASA initiative has been launched called SIMBIOS to combine data products from the various international ocean color missions in a manner which ensures the best possible global coverage and optimum exploitation of the complementarity of the sensors. These data are expected to provide a continuous time series of measurements for the study of ocean productivity issues including climate variability.

◆ *Air/Sea Fluxes:* Measurements of air/sea fluxes are required for ocean and atmosphere regional/global climate models. At present, the predictive capability of coupled climate models is limited because they do not give correct air/sea fluxes. The parameters to compute the global air/sea fluxes are being determined from space-based observations. Focus is on transfer of carbon and dimethyl-sulfide (DMS) compounds.

◆ *Coastal Resource Management:* Research is supported to develop key tools for regional resource management. As resource management requires near-real-time and frequent observations, techniques are being developed to link observations from various satellites. The color of the ocean has been difficult to interpret in a useful manner in the past, and this program is developing new technologies and models to address this situation.

◆ *Technology and Algorithm Development:* Continuing emphasis is placed on the development of future instruments, particularly hyperspectral instruments for *in situ*, aircraft, and satellite platforms. Algorithm research is directed toward understanding turbid waters and turbid atmospheres in order to retrieve useful information better from remote sensing data.

Physical Oceanography Program

GOAL:

Understand and determine the role of ocean processes in seasonal-to-interannual and longer climate variations with a particular emphasis of the use of space-based ocean observations.

STRATEGY:

Use existing and future space-based observations to measure quantitative variations in the ocean circulation, sea surface temperature, tides and mean sea level, sea surface winds, and air-sea fluxes. Transition technologies to the general research and operational communities as rapidly as possible. Space-based ocean observations provide global coverage but only indirect subsurface information. In contrast, *in situ* observations give good sampling of the vertical water column, but have poor temporal and geographic distribution. Numerical models can be used to combine or assimilate disparate observation types into integrated descriptions of the state of the ocean on a regular spatial and temporal grid.

ELEMENTS:

- *Ocean Circulation:* Satellite altimeters offer the only global observations of the ocean circulation. The very precise TOPEX/Poseidon measurements are being used to study basin-scale ocean dynamics, mesoscale energetics, ENSO and related extratropical phenomena, the southern ocean including the Antarctic Circumpolar current, and western boundary currents.

- *Surface Wind Vectors:* Space-based observations are providing information for air-sea fluxes needed for global ocean and climate models. The present predictive capability of coupled climate models is limited by a lack of adequate air-sea flux and wind stress data from *in situ* sources. Scatterometer measurements of wind speed and direction (NSCAT and others) provide critically needed global data sets.

- *Tides and Mean Sea Level:* Global ocean tides are best determined from the precise global measurements of sea surface height made by TOPEX/Poseidon and successors. Non-tidal trends and variations of sea level are important indicators of climate change.

- *Technology and Algorithm Development:* Continued development is needed to produce improved/cheaper satellite instruments A polarimetric passive microwave radiometer, capable of measuring both wind speed and direction, is being developed.

MILESTONES:

- Improved ephemerides and algorithms are being used in a consistent reanalysis of all altimeter data from 1978, including the recently declassified Geosat data. Tests have shown that the error of sea surface height measured by Geosat is reduced from about 1/2 meter to about 10 cm.

- TOPEX/Poseidon data have revealed westward propagating Rossby waves in the Pacific at high latitudes. Phase speeds differ from theoretical, indicating that the theory may need to be revised.

- Global mean sea level rise of 3–5 mm/yr. has been determined from three years of TOPEX/Poseidon altimeter data, with large interannual variation due to regional fluctuations. The latter are strongly correlated with sea surface temperature, and are revealing new information concerning upper ocean thermal content.

- Integrated, internally consistent model-assimilated ocean/atmosphere/ice datasets: Space-based, air-borne, and ground-based measurements will be combined through numerical models to provide research quality gridded data sets for use in climate diagnostics and sensitivity studies.

Polar Research Program

GOAL:
Measuring the mass balance of the Greenland and Antarctic ice sheets; and improving the simulation of ocean/ice/atmosphere processes in climate models.

STRATEGY:
Development of improved techniques for estimating important geophysical paremeters from satellite and *in situ* data, investigation of key processes and their mutual interaction, and development of models that incorporate our improved understanding.

ELEMENTS:

◆ *Ice-Sheet Mass Balance:*

a. Satellite radar altimetry, aircraft laser altimetry, and some day GLAS data to measure thickness changes of terrestrial ice.
b. Passive-microwave data to monitor surface melt extent on the ice sheets, and to infer snow temperatures and snow-accumulation rates.
c. Satellite SAR to compile first high-resolution maps of Greenland and Antarctica, to detect changes in ice morphology, and to measure ice motion.
d. Investigations of surface energy balance, ice dynamics etc using satellite data, automatic weather stations, and field research.
e. Use results of “change” observations and process studies to improve theoretical models of ice response to climate changes.

◆ *Ocean/Ice/Atmosphere Processes*

a. Assimilation of passive-microwave, SAR, AVHRR, and TOVS data and *in situ* measurements into process models to provide estimates of, and ultimately to monitor, sea-ice characteristics: extent; concentration; thickness distribution; motion; snowcover; albedo; temperatures; winds; cloud cover.
b. Use the above to estimate fluxes of energy, water, and brine via simple models.
c. Assess impact of these fluxes on ocean and atmosphere via coupled models.
d. Investigate sensitivity of GCM results to perturbations in these fluxes.
e. Improve GCM parameterization of these processes.

RELATIONSHIP TO EOS:

◆ Much of this program addresses ocean, ice, and atmosphere fluxes, and all this work is closely coordinated with relevant EOS IDPs. Associated algorithm development has direct relevance to data from EOS sensors.

◆ The ice sheet mass balance program is developing early data sets against which GLAS data can be compared soon after launch in 2001, providing “change” estimates five or more years earlier than otherwise possible. Our laser-altimetry work contributes directly to algorithm development for GLAS—work that otherwise could not be done without major EOS investment.

Radiation Science Program

GOAL:
To observe and accurately calculate the radiative flux divergence's (heating and cooling rates) at all relevant space-time scales and for all major processes that produce radiative forcing and feedback's in the Earth's climate system.

STRATEGY:
Conduct observational and theoretical investigations of major radiative elements of the Earth's climate system and radiative forcing parameters, field experiments and modeling studies of major feedback mechanisms, and analysis and validation of space observations for radiative parameters and processes.

ELEMENTS:

◆ *Clouds and Radiation:* Emphasis is on the role of clouds in the Earth's radiation budget and in climate change. Sub-elements include studies which utilize the cloud and radiation data set developed by the International Satellite Cloud Climatology Project (ISCCP) and the series of regional cloud/radiation field experiments referred to as the First ISCCP Regional Experiments (FIRE). Through program support, FIRE scientists: conduct comprehensive field measurements, data analysis, and modeling of the radiative characteristics and life-cycle mechanisms for mid-latitude and tropical cirrus, marine stratocumulus, and Arctic cloud systems. Observations are provided by advanced technology instruments on satellite and airborne platforms, and on the surface.

◆ *Radiation Budget:* Earth Radiation Budget Experiment (ERBE) instruments on three satellites have produced an accurate long-term climatology of the radiation energy budget at the top of the Earth's atmosphere. Scientific investigations based on ERBE observations, focus on understanding the spatial and temporal characteristics of the radiation balance between Sun, Earth, atmosphere, and space. They are also used to validate and improve climate models, and to study cloud and radiation interactions.

◆ *Surface Radiation:* Satellite and surface based radiation measurements are being used to produce and validate a global Surface Radiation Budget (SRB) climatology. This climatology of the shortwave and longwave radiation fluxes at the surface are used in analyses of their seasonal and geographic variation and their relationship to cloud radiation forcing. Validation studies utilize the measurements provided by the international Baseline Surface Radiation Network (BSRN) and the Global Energy Budget Archive (GEBA).

◆ *Aerosols and Radiation:* Focus is developing an understanding of the radiative consequences of atmospheric aerosols (primarily troposphere) through Lidar observations and intensive field observations. Lidar observations have been provided by a network of surface based systems and from space by the Laser In-space Technology Experiment (LITE) on STS-64. Also included in this element is a series of Smoke, Clouds, and Radiation (SCAR) regional field experiments to study the direct and indirect (cloud related) radiation effects of smoke, sulfate aerosols from fossil fuel, and biomass burning.

Associated EOS Interdisciplinary Studies: *Clouds and Earth's Radiant Energy System* (B. Wielicki, et al.; LaRC), *Climate Processes Over the Oceans* (D. Hartmann, et al.; University of Washington), and *Characterizing Aerosol Forcing Over the Atlantic Basin* (B. Holben, et al.).

Resource Vulnerability Assessment Program

GOAL:
To develop a set of global change observations and indicators which provide early warning and trend information on resource vulnerability issues which directly impact humans through a focus on the direct connection of present and future global observing system data (particularly space-based) to socioeconomic applications and natural resource management.

STRATEGY:
To utilize appropriate satellite and *in situ* physical sciences data and observations combined with socio-economic data and information to develop resource vulnerability indicators in a number of areas of direct impact to or by humans such as land use/land cover change, human health, fresh water management, sustainable use of natural resources, food, refugees, natural hazard disaster mitigation, UV radiation at the Earth's surface, and hazardous wastes and pollution. The emphasis of these studies is to improve the understanding of the interactions between human and natural Earth systems through combined studies in the natural sciences and social sciences involved in global environmental change.

ELEMENTS:

- ◆ Integrate data from satellites, demographic censuses, and field surveys to understand the human dimensions of deforestation and regrowth in land use/land cover change studies, including such factors as changes in population, migration, demographic structure, policies, economies, land tenure, investment, agrarian law.

- ◆ Study long-term reconstructions/projections of population change, economic activities, technological developments, and institutional changes - and their relationships to flows of energy, materials, and trace gases emanating from land use and production-consumption relationships—in important "regional" (about one equatorial degree in size) locations

- ◆ Assess the degree, as well as the strengths and weaknesses, of the use of remote sensing and other scientific information on ENSO in various economic sectors in one of the countries most directly affected by ENSO events, Peru.

- ◆ Investigate the application of remote sensing data and information to the understanding of the relationships between human health and the environment.

- ◆ Assess the links between local economic and population changes and global environmental change through (1) Earth system data and models to better understand the ways changes in population, economy, and technology produce local changes in gases, aerosols, and land cover and (2) linked social science studies of how population, economy, technology, institutions, culture, and behavior account for temporal changes in environmental impacts.

- ◆ Investigate an assessment of the biogeochemical and socioeconomic factors that determine the release, storage, and flows of nitrogen in China and the United States.

- ◆ Investigate how remotely-sensed data can be integrated with other types of spatial data and crop models to improve understanding of ENSO-crop relationships, to forecast yields, and to evaluate agronomic adaptive strategies.

- ◆ Develop an urban/regional spatial data base on global change information to test scientific models and remote sensing sensors for use by scientists; land use managers; environmental protection managers; regional, local, and city planners; and resource consultants.

Terrestrial Ecology Program

GOAL:
To improve understanding of the structure and function of global terrestrial ecosystems, their interactions with the atmosphere and hydrosphere, and their role in the cycling of the major biogeochemical elements and water.

STRATEGY:
Use remote sensing to observe the distribution and structure of the Earth's terrestrial ecosystems, conduct process studies to elucidate ecosystem function, and develop realistic models that simulate these ecosystem properties and processes. Emphasis is on integrating process understanding with remote sensing observations and ecological modeling to extend understanding across spatial and temporal scales.

ELEMENTS:
- ◆ Develop models describing the relationships between land surface characteristics (e.g., ground cover, LAI, biomass, vegetation height and structure, canopy chemistry) and remotely-sensed information.

- ◆ Incorporate remotely sensed data into models of ecosystem processes, using available models and relationships between the fluxes of electromagnetic radiation and land surface characteristics, to determine spatial and temporal changes in terrestrial ecosystems.

- ◆ Measure CO_2 fluxes and changes in above- and below-ground biomass for land surfaces, and develop process models to calculate CO_2 fluxes and changes in the carbon balance of ecosystems.

- ◆ Measure trace gas fluxes; characterize the environmental factors affecting them, the processes involved, and the extent to which these are affected by changes in land use and land surface characteristics; and develop biogeochemical cycling models.

- ◆ Utilize the capacity and flexibility of NASA's research program to mount periodic field campaigns (e.g., BOREAS) featuring *in situ,* aircraft-based, and satellite-based measurements focused on a particular problem or set of problems.

- ◆ Develop quantitative understanding of remotely sensed signals (i.e., reflectance, scattering, and emission of electromagnetic radiation from terrestrial ecosystems) and the techniques to interpret sensor data, including rigorous estimates of accuracy and quantification of errors and with an aim toward exploiting data from EOS, Lewis, RADARSAT, and other near-term missions.

Tropospheric Chemistry Program

GOAL:

To develop an understanding of global tropospheric chemistry and assess the susceptibility of the global atmosphere to chemical change from human impacts and natural effects with special attention to the connection of chemical change to climate change and to changes in atmospheric ozone.

STRATEGY:

Determine tropospheric meteorological/chemical influences on the atmosphere as a whole, particularly the stratosphere and upper troposphere; understand the chemistry of global tropospheric species and the causes of changes in chemical composition, particularly in regions of the world that are expected to experience the greatest stree from human impacts over the next decade; develop techniques for remote and *in situ* measurement of the concentrations and fluxes of key tropospheric species; and develop and a strategy for chemical measurements from space platforms in combination with *in situ* measurement techniques.

ELEMENTS:

- Develop instruments that have the sensitivity and reliability to meet the severe measurement requirements of global tropospheric chemistry.
- Conduct aircraft and ground based measurement campaigns, supported after the campaigns by extensive analysis efforts, in regions of the world where the rates of change of atmospheric composition from human impacts are expected to be large and, therefore, most readily observable.
- Develop and refine strategies for combining *in situ* measurements with space measurements in the most effective manner.

Upper Atmosphere Research Program

GOAL:
To understand the physical, chemical, and transport processes of the atmosphere (upper troposphere and stratosphere) and their control on the distribution of stratospheric species such as ozone; to accurately assess possible perturbations to the composition of the stratosphere caused by human activities and natural phenomena; to understand the distribution of and processes affecting the concentrations of radiatively active species and the processes responsible for the dynamical and chemical coupling of the troposphere and stratosphere.

STRATEGY:
Field measurements employing *in situ* and remote sensing techniques from surface-based, aircraft, balloon, and rocket platforms which are supported by laboratory studies of gas phase and heterogeneous kinetics, photochemistry, spectroscopy, and calibration standards development, as well as process oriented modeling and data analysis.

ELEMENTS:

- ◆ Field measurement campaigns to measure the morphology of trace chemical species and dynamical quantities as functions of altitude, latitude, and season in order to help determine patterns and rates for global-scale atmospheric transport and photochemical interconversion.

- ◆ Continued implementation of an international ground-based remote-sensing measurement Network for the Detection of Stratospheric Change (NDSC) which provides ozone profiles as well as other atmospheric trace constituents and parameters.

- ◆ Support of the Advanced Global Atmospheric Gases Experiment (AGAGE) network, which has been providing long-term, high-frequency, and high-accuracy ground-based monitoring of many key halogen-containing compounds, plus CH_4, CO, and N_2O, which impact climate and atmospheric ozone.

- ◆ Laboratory studies of heterogeneous processes that occur on polar stratospheric cloud particles and sulfate aerosols and of photochemical processes that govern the partitioning of active and reservoir species and the atmospheric degradation for CFC replacement compounds. Also, spectroscopic measurements in support of satellite, aircraft and balloon programs.

- ◆ Provide correlative measurements to support analysis and validation of satellite data.

- ◆ Development of new technological ideas, techniques, and instruments for use in atmospheric research.

- ◆ Provide support for externally sponsored assessments such as WMO/UNEP Ozone Assessment and the IPCC Climate Change Assessment, as well as for the assessment of the Atmospheric Effects of Aviation Project.

Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS)

GOAL:

Between 1996 and 2001, there are seven ocean color satellite missions (SeaWIFS, OCTS, POLDER, MODIS (AM and PM), MISR, MERIS, and GLI) plus several more experimental missions (ROSCAT, UVISI, and the two MOS sensors) scheduled for launch that are capable of providing routine ocean color data over large portions of the global ocean. The goal of the special NASA initiative, SIMBIOS, is to develop a methodology and operational capability to combine data products from these various ocean color missions in a manner that ensures the best possible global coverage and best exploits the complementary missions of the sensors.

STRATEGY:

The various proposed ocean color sensors are highly complementary and congruent in many important respects, but also exhibit significant differences in technical approach which have implications in algorithm and data product performance. A major challenge is to achieve data compatibility, and differences among the missions must be resolved or explained at the level of major derived bio-optical products, with sufficient documentation to allow future scientists to relate their measurements to the ones obtained n the mid-1990s to 2001 and beyond.

The strategy to accomplish this is three-fold: 1) to quantify the relative accuracies of the products from international ocean color missions; 2) to improve the level of confidence and compatibility among the products; and 3) to generate merged, improved level-3 products. The strategy will be implemented through the SIMBIOS Project Office at Goddard Space Flight Center and by a series of principal investigator-led studies solicited by a NASA Research Announcement issued on July 15, 1996.

ELEMENTS:

The SIMBIOS project encompasses both experimental and operational requirements with links to all the missions, but will have a separate management and facility structure. These activities have been organized into four basic components, namely sensor calibration, product and algorithm validation, data merging, and operational data processing. All components are connected (and in some cases overlap) and each illustrates the process of product development, assessment and refinement which is central to the SIMBIOS project.

There are four main elements of the SIMBIOS Program:

- *The SIMBIOS Project Office:* A SIMBIOS Project Office is being established to provide support and cordination for the SIMBIOS Project such as administrative support, support for project documentation, the data processing system, the support for each of the elements, overseeing any data processing system supported by the project, and overseeing coordination of round robin experiments and measurement protocol development.

- *Sensor Calibration:* The objective of the SIMBIOS calibration program is to review pre-launch, on-orbit, and vicarious calibration data provided by the mission projects, to complement the calibration activities of the mission projects, and to integrate various calibration datasets and provide the best calibration and algorithm coefficients possible, including uncertainties.

- *Data Product Validation:* A primary objective of the SIMBIOS program is the identification and elimination of biases between regions and between mission data sets of the SIMBIOS-related missions. The SIMBIOS validation program will be accomplished by principal investigator-led data collection and analysis studies and field data archival and satellite data processing activities acquired through the SIMBIOS NRA selection process. It is anticipated that validation activities will be focused on data products such as water leaving radiance, pigment concentration, chlorophyll-a concentration, ocean water attenuation coefficient, ocean aerosols, photosynthetically active radiation, suspended solids concentration, coccolith concentration, absorption coefficient and gelbstoffe, chlorophyll fluorescence, ocean productivity, phycoerythrin contration.

- *Data Merging:* The objective of the data merging component of the SIMBIOS project is to develop and test merging algorithms that can be applied routinely to produce improved time series of geophysical variables provided by the various ocean color missions. These products include chlorophyll-a concentration, aerosol content, colored-dissolved organic matter, and primary production. Principal investigator-led studies will address not only time series, but also regional-to-global datasets.

Appendix 3
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Appendix 4
Acronyms and Abbreviations

AAOE Airborne Antarctic Ozone Experiment
AASE Airborne Arctic Stratospheric Expedition
ACE Aerosol Characterization Experiment
ACMAP Atmospheric Chemistry and Modeling Analysis Program
ACSYS Arctic Climate System Study
ADEOS Advanced Earth Observation Satellite (Japan)
AEAP Atmospheric Effects of Aviation Program
AESA Atmospheric Effects of Stratospheric Aircraft Program
AGAGE Advanced Global Atmospheric Gas Experiment
AGCM Atmospheric General Circulation Model
ALE Atmospheric Lifetime Experiment
AMIP Atmospheric Model Intercomparison Project
ASHOE Airborne Southern Hemisphere Ozone Experiment
ATLAS Atmospheric Laboratory for Applications and Science
ATMOS Atmospheric Trace Molecule Spectroscopy
ATSR Along Track Scanning Radiometer (ESA)
AVHRR Advanced Very High Resolution Radiometer

BAHC Biological Aspects of the Hydrological Cycle (IGBP)
BOREAS Boreal Ecosystem Atmospheric Study

CFC Chlorofluorocarbon
CHEM Chemistry Mission
CHEM Earth Observing System Chemistry Launch (2002)
CLIVAR Climate Variability (and Predictability International Program)
COADS Comprehensive Ocean-Atmosphere Data Set
COARE Combined Ocean-Atmosphere Research Experiment
COLA Center for Ocean-Land-Atmosphere (IGES)
CRISTA/SPAS Cryogenic Infrared Spectrometer and Telescopes for the Atmosphere/Shuttle Pallet Satellite
DAAC Distributed Active Archive Center
DAO Data Assimilation Office (NASA/GSFC)
DOD Department of Defense
DOE Department of Energy

ENVISAT Environmental Satellite
ENSO El Niño-Southern Oscillation (Phenomenon)
EOS Earth Observing System
EOS-AM Earth Observing System "AM" Launch (1988)
EOS-PM Earth Observing System "PM" Launch (2000)
EOSDIS EOS Data Information System
EPA Environmental Protection Agency
ERAST Environmental Research Aircraft and Sensor Technology Program
ERBE Earth Radiation Budget Experiment
ERS-1 European Research Satellite-1
ERS-2 Environmental Remote Sensing Satellite-2
ESSP Earth System Science Pathfinders

FAA Federal Aviation Administration
FIFE First ISLSCP Field Experiment
FIRE First ISCCP Regional Experiment
FSD Flight Systems Division

GAIM Global Analysis, Interpretation, and Modeling (Program)
GAME GOALS Asian Monsoon Experiment
GCIP GEWEX Continental-Scale International Project
GCM General Circulation Model
GCOS Global Climate Observing System
GCSS GEWEX Cloud System Study
GEIA Global Emissions Inventory Activity
GEWEX Global Energy and Water Cycle Experiment
GIM Global Intergration and Modeling
GIP Guest Investigator Program
GISS Goddard Institute for Space Studies (NASA)
GLA Goddard (Space Flight Center) Laboratory for Atmospheres
GLOCHEM Global Observations of Atmospheric Chemistry
GOALS Global Ocean-Atmosphere-Land System

(Program)
GOME Global Ozone Mapping Experiment
GOMOS Global Ozone Monitoring by Occultation of Stars
GOOS Global Ocean Observing System
GPCP Global Precipitation Climatology Project
GSFC Goddard Space Flight Center (NASA)
GTE Global Tropospheric Experiment
GTOS Global Terrestrial Observing System
GVaP GEWEX Water Vapor Project

HCFC Hydrochlorofluorocarbons
HIRDLS High-Resolution Dynamics Limb Sounder
HIRIS High Resolution Imaging Spectrometer
HPCC High Performance Computing and Communications
HSRP High Speed Research Program

IDS Interdisciplinary Science Program
IGAC International Global Atmospheric Chemistry
IGAP International Global Aerosol Program
IGBP International Geosphere-Biosphere Programme
IGN International Geodedic Network
IGOS Integrated Global Observing Strategy
ILAS Improved Limb Atmospheric Spectrometer
IMG Interferometric Monitor for Greenhouse Gases
IPCC Intergovernmental Panel on Climate Change
IRI International Research Institute
ISCCP International Satellite Cloud Climatology Project
ISLSCP International Satellite Land Surface Climatology Project
ISTOK-1 Infrared Spectroradiometer on *Mir*

JGOFS Joint Global Ocean Flux Study
JPL Jet Propulsion Laboratory

LBA Large Scale Biosphere-Atmosphere Experiment in Amazonia
LDEO Lamont-Doherty Earth Observatory (Columbia University)
LIMS Limb Infrared Monitor of the Stratosphere

MAESA Measurements for Assessing the Effects of Stratospheric Aircraft
MAHRSI Middle Atmosphere High Resolution Spectrograph Investigation
MAPS Measurement of Air Pollution from Satellites
METOP Meteorological Operational Weather Satellite
MIPAS Michelson Interferometer for Passive Atmospheric Sounding
MIRAS *Mir* Infrared Atmospheric Sounder
MIRIAM/DOPI *Mir* Infrared Atmospheric Measurements/Double Pendulum Interferometer
MLS Microwave Limb Sounder
MO&DA Mission Operations and Data Analysis
MODIS Moderate-Resolution Imaging Spectroradiometer
MOPITT Measurement of Pollution in the Troposphere
MSX Midcourse Space Experiment
MTPE Mission to Planet Earth

NARSTO North American Research Strategy for Troposheric Ozone
NASA National Aeronautics and Space Administration
NCAR National Center for Atmospheric Research
NCEP National Center for Environmental Prediction (NOAA)
NDSC Network for the Detection of Stratospheric Change
NDVI Normalized Difference Vegetation Index
NEG Numerical Experimentation Group (of CLIVAR)
NESDIS National Environmental Satellite and Information Service
NMP New Millenium Program
NOAA National Oceanic and Atmospheric Administration
NPOESS National Polar Orbiting Environmental Satellite System

NRA NASA Research Announcement
NSCAT NASA Scatterometer
NSF National Science Foundation

OCTS Ocean Color Temperature Sensor (Japan)
ODIS Operations Data and Information Systems
ODU.S. Ozone Dynamics Ultraviolet Spectrometer
OLME Ozone Layer Monitoring Experiment
OLR Outgoing Longwave Radiation
OMTPE Office of Mission to Planet Earth
ONR Office of Naval Research
OZON-MIR Ozone Trace Gas and Aerosol Monitor on *Mir*

PACS Pan American Climate Study (GOALS)
PEM Pacific Exploratory Mission
PILPS Project for Intercomparison of Land Surface Parameterization Schemes
POAM Polar Ozone and Aerosols Mission
POLARIS Photochemistry of Ozone Loss in the Arctic Region in Summer

QBO Quasi-Biennial Oscillation

RIS Retroreflector in Space

SAGE Stratospheric Aerosol and Gas Experiment
SASS Subsonic Assessment
SCIAMACHY Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
SCSMEX South China Sea Monsoon Experiment
SBUV/2 Solar Backscatter Ultraviolet spectrometer/2
SeaWIFS Sea-Viewing Wide Field Sensor
SMIP Seasonal Model Intercomparison Project
SMMR Scanning Multichannel Microwave Radiometer
SOLSE Shuttle Ozone Limb Sounder Experiment
SONEX Subsonic Ozone and Nitrogen Experiment
SPADE Stratospheric Photochemistry, Aerosols and Dynamics Expedition
SPARC Stratospheric Processes And their Role in Climate
SRB Surface Radiation Budget
SSBUV Shuttle Solar Backscatter Ultraviolet spectrometer
SSM/I Special Sensor Microwave/Imager
SST Sea Surface Temperature
STRAT Stratospheric Tracers of Atmospheric Transport

TAO TOGA Automated Observation
TARFOX Tropospheric Aerosol Radiative Forcing Experiment
TCP Tropospheric Chemistry Program
TES Tropospheric Emission Spectrometer
TOGA Tropical Ocean-Global Atmosphere (Program)
TOMS Total Ozone Monitoring Spectrometer
TOTE Tropical Ozone Transport Experiment
TPFO TOPEX/Poseidon Follow-On (Mission)
TRACE Transport and Atmospheric Chemistry Experiment
TRMM Tropical Rainfall Measurement Mission

UARP Upper Atmospheric Research Program
UARS Upper Atmospheric Research Satellite
UAV Uncrewed Aerial Vehicles
UCLA University of California, Los Angeles
UNEP United Nations Environment Program
USGRP U.S. Global Change Research Program
UV Ultraviolet
UVISI Ultraviolet and Visible Imagers and Spectrographic Imagers

VOTE Vortex Ozone Transport Experiment

WCRP World Climate Research Program
WGNE Working Group on Numerical Experimentation (WCRP)
WMO World Meteorological Organization
WOCE World Ocean Circulation Experiment

Appendix 5
Reference URLs

ADEOS http://hdsn.eoc.nasda.go.jp/guide/guide/satellite/satdata/adeos_e.html
AGAGE http://cdiac.esd.ornl.gov/cdiac/ndps/db1001.html
ATLAS http://wwwghcc.msfc.nasa.gov/atlas.html
ATMOS http://remus.jpl.nasa.gov/
CLIVAR International Program http://www.clivar.ucar.edu/hp.html
DAACs http://eosdis.larc.nasa.gov/handbook/daac_glossary.html
DC-8 http://airsci-www.arc.nasa.gov/DC-8/dc8page.html
EOS http://spso.gsfc.nasa.gov/spso_homepage.html
EOSDIS http://spsosun.gsfc.nasa.gov/ESDIShome.html
EOSDIS http://observer.gsfc.nasa.gov
EOS/IDS http://spso.gsfc.nasa.gov/directory/ids/ids.html
ENVISAT http://gds.esrin.esa.it/Ce3.1.3;sk=F1A64C9E
ER-2 http://airsci-www.arc.nasa.gov/ER-2/AIRPROGL.HTM
ESA http://gds.esrin.esa.it:80/home;sk=F1A64C9E
GCOS http://jpo@gcos.wmo.ck
GEWEX International Program http://www.cais.com/gewex/gewex.html
GOME http://www.jw.estec.esa.nl:8080/gome.index.html
IGAC http://web.mit.edu/igac/www/
IGBP International Program http://www.igbp.kva.se/
ISCCP http://haboob.giss.nasa.gov
LITE http://arbs8.larc.nasa.gov/LITE/litehome.html
MAPS http://stormy.larc.nasa.gov/overview.html
MSX http://msx.nrl.navy.mil/
NASA http://www.nasa.gov/
NASA/GSFC Data Assim. Office http://hera.gsfc.nasa.gov/dao.home_page.html
NASA/GSFC Earth Sciences Directorate http://sdcd.gsfc.nasa.gov/ESD/
NASA/Office of Mission to Planet Earth http://www.nasa.gov/office/mtpe
National Center for Atmospheric Research (NCAR) http://www.ucar.edu/org/ncar/index.html
NDSC http://climon.wwb.noaa.gov/
NOAA/Climate and Global Change Program http://www.noaa.gov/ogp/c&gc.html
OMTPE http://www.hq.nasa.gov/office/mtpe/
PRIRODA http://www.ire.rssi.ru/priroda/priroda.htm
Russian Academy of Sciences http://www.RAS.ru/RAS/index.html
SAGE http://asd-www.larc.nasa.gov/sage/ASDsage.html
Satellilite Weather Information for Stratospheric Sciences (SWISS) http://telsci.arc.nasa.gov/pages/tote1.html
Source for climate data and information http://gcmd.gsfc.nasa.gov/pointers/meteo.html
Space Research Institute/Russian Academy of Sciences http://www.iki.rssi.ru/Welcome.html
SPARC http://www.sparc.com/
SSBUV http://ssbuv.gsfc.nasa.gov/
STRAT http://hyperion.gsfc.nasa.gov/Aircraft/strat/strat.html

TARFOX http://prometheus.arc.nasa.gov/~tarfox/
THESEU.S. http://www.hq.nasa.gov/office/mtpe/Theseus.html
TOMS http://jwocky.gsfc.nasa.gov/
UARS http://daac.gsfc.nasa.gov/CAMPAIGN_DOCS/UARS_project.html
USGCRP http://www.usgcrp.gov
US Global Change Research Program http://www.usgcrp.gov/
VOTE/TOTE http://hyperion.gsfc.nasa.gov/Aircraft/tote/vote_top.html